N:o 433 1943 Mars—April

# GEOLOGISKA FÖRENINGENS

I

STOCKHOLM

# FÖRHANDLINGAR

Utgivare: Gustaf Troedsson

BAND 65

HÄFTE 2.

## Innehåll:

Sid.

*Uppsatser:* Mason, B. Mineralogical aspects of the system FeO-$Fe_2O_3$-MnO-$Mn_2O_3$ 97
Rytterberg, E. Åsliknande grusryggar i trakten NV och V om Avesta 181
Ljungner, N. Isdelarstudier vid polcirkeln . . . . . . . . . . . . . . 198

*Notis:* Bergdahl, A. Diabasgångar och gångdalar i trakten av Tisaren . . . . 211

***Mötet den 4 mars 1943.*** Revisionsberättelse. E. Ljungner: Isdelarstudier vid polcirkeln 217

***Mötet den 10 mars 1943.*** G. Lundqvist: Den regionala fördelningen av Norrlands lösa jordarter . . . . . . . . . . . . . . . . . . . . . . . . . . . 219

***Mötet den 1 april 1943.*** H. Hedström: Minnesord över Sir Henry Miers och Frank Dawson Adams. O. Adamson: En oversikt over det alkaline bergartsområde ved Norra Kärr i Småland . . . . . . . . . . . . . . . . . . 220

*Geolognytt* . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 221

***Författarna äro ensamma ansvariga för sina uppsatsers vetenskapliga innehåll.***

STOCKHOLM 1943
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER
430060

**Pris för detta häfte Kr. 5: —**

EN GOD BILD

kompletterar texten och ger ökad åskådlighet åt innehållet.

Av stor vikt är därför att Edert bildmaterial gives det reproduktionsförfarande som är lämpligast.

Vi som ha mångårig erfarenhet och specialiserat oss på vetenskapliga arbeten kunna därför ge Eder det bästa rådet.

A.-B. KARTOGRAFISKA INSTITUTET
ESSELTE A.-B.

VASAGATAN 16
STOCKHOLM

Telefon: Namnanrop: »Centraltryckeriet»

---

Leitz

**Optiska Instrument för mineralogi och petrografi.**
**Leica-Kameran — Prismakikare.**
**Lupper.**

---

**Generalagent för Leitz optiska instrument**

AXEL LUNDQVIST A.-B.
DROTTNINGGATAN 28 - STOCKHOLM
Tel.: 10 87 30 — 21 01 81

GEOLOGISKA FÖRENINGENS
I STOCKHOLM
FÖRHANDLINGAR.
BAND 65. HÄFT. 2. N:o 433.

# Mineralogical aspects of the system $FeO - Fe_2O_3 - MnO - Mn_2O_3$.

By

BRIAN MASON.

## CONTENTS.

Page

Introduction . . . . . 97

The iron oxides

$FeO$ — Wüstite . . . . . 101
$Fe_3O_4$ — Magnetite . . . . . 104
$Fe_2O_3$ — Maghemite and Hematite . . . . . 106
The system $FeO$-$Fe_2O_3$ . . . . . 119

The manganese oxides

$MnO$ — Manganosite . . . . . 129
$Mn_3O_4$ — Hausmannite . . . . . 130
$Mn_2O_3$ — Bixbyite. . . . . 132
$3Mn_2O_3 \cdot MnSiO_3$ — Braunite . . . . . 135
The system $MnO$-$Mn_2O_3$ . . . . . 139
The system $FeO$-$MnO$ . . . . . 142
The system $Fe_3O_4$-$Mn_3O_4$ . . . . . 145
The system $Fe_2O_3$-$Mn_2O_3$ . . . . . 168
Summary and conclusions . . . . . 174
List of references . . . . . 176

## Introduction.

In terms of the classical mineralogy it might well be thought that the ron and manganese oxide minerals offer little scope for fundamental research. From a narrowly descriptive viewpoint our knowledge of these minerals appeared to be largely complete at the end of last century. To many at that time mineralogy seemed to be approaching the stage of a worked-out science. However, the advances in physical chemistry n the past forty years, especially in that branch dealing with the solid state, have revolutionized and revitalized mineralogy. The determination of crystal structures by means of X-rays, and the study of the mutual relationships between the phases and components of a chemical system have led to a new concept of a mineral species. The fundamental characteristic of a mineral is that it is an independent phase of a physicochemical system, occurring in the earth's crust. Knowledge of atomic structure has given a solid base to the idea of isomorphism, and the possibility of replacement of atoms of one element by atoms of another is now realized to be much greater than was formerly believed. The interdependence of physical chemistry and mineralogy has become more and more clear. It is still perhaps insufficiently realized, however, the important part mineralogical studies have to play in the elucidation of chemical reactions under conditions which we cannot reach in the laboratory. Not only are conditions of temperature and pressure in nature often such that they cannot be reproduced in the laboratory, but the time factor plays an extremely important, if often overlooked, part. Equilibrium, sometimes slow to be reached in gaseous and liquid systems, in solid systems is often unattainable under the time limitations of laboratory studies. Here investigation of minerals can often reveal that laboratory products, although apparently in equilibrium under normal conditions, are actually in a metastable state.

It is thus clear that a sufficient knowledge of a mineral demands a sufficient knowledge of the physicochemical conditions under which it can be formed and under which it can exist as a stable phase. With this in mind it is sobering to study a textbook of mineralogy and to see for how few species the above holds good. It is on these grounds that this study of the system $FeO$-$Fe_2O_3$-$MnO$-$Mn_2O_3$ has been made, in the hope that it would result in a clearer insight into the different mineral species and their interrelations, especially the limits of isomorphous replacement. In this way it has been possible to give a certain quantitative expression to the limits of the various species and to effect some simplification and clarification in the complicated nomenclature of this group, from which a dozen or more minerals have been described as individual species. Several of these so-called individual species have proved to be synonymous. At the same time it has been possible from the investigation of the minerals to extend the present knowledge of the phase relations between the different components in the system. Last, but by no means least important, an attempt has also been made to correlate the parageneses of the minerals with their physical and chemical features.

By the nature of this investigation, much effort had to be given to a critical selection and interpretation of the mass of data — much of it excellent, but much also of doubtful reliability — resulting from earlier investigations. The result is that a large part of the first half of this paper, dealing with the individual components, is a survey with new work only where it seemed called for in order to elucidate doubtful points or to supplement the existing information. In this connection I believe I have covered the literature exhaustively, but the literature on the iron and manganese oxides is so extensive that it is out of the question to claim that nothing has been overlooked. In addition, the state of war in the past three years has largely prevented the interchange of scientific publications, so foreign developments in this subject since 1940 are to a great extent unknown to me.

The experimental work in connection with this investigation is described in the main body of the paper. A few words may, however, be inserted here on the X-ray methods used. Most of the X-ray work was by means of powder photographs, which were used for the identification of the different phases, for the determination of the relationships between lattice dimensions and composition in the various systems, and for the fixing of phase boundaries. The cameras used for making the powder photographs were of the Seeman-Bohlin focussing type as designed by Phragmén. Chromium radiation was employed. In routine work the accuracy of measurement of the lattice dimensions was ± 0.1 %. This is sufficient for most purposes, and unless otherwise stated is the accuracy of the measurements given in this paper. When desirable, however, an accuracy of ± 0.05 % was attainable by taking special precautions.

All temperatures are in degrees Centigrade.

A few words are also necessary on the conception of solid solution. As used in this paper this term is applied to two essentially distinct phenomena. The first is the classical solid solution, in which there is replacement of one atom by another of the same kind. This is exemplified by jacobsite, which is $Fe_3O_4$ with some of the iron atoms replaced by manganese, and can be looked upon as a solid solution of $Mn_3O_4$ in $Fe_3O_4$. The second is of the kind referred to as »solid solutions of $Fe_2O_3$ in $Fe_3O_4$» and similar cases where the numbers of atoms in the two phases are not the same. Here there is clearly no replacement of one atom by another of the same kind. Instead of a replacement there is a removal of iron atoms from the lattice of $Fe_3O_4$, thus leading to an excess of oxygen over the stoichiometric formula. Similarly wüstite, which always contains more oxygen than corresponds to the formula FeO, should not be regarded as a solid solution of $Fe_3O_4$ in FeO, being actually FeO with a deficient iron lattice. A familiar example is pyrrhotite, which had long been looked upon as a solid solution of S in FeS, until X-ray studies showed that it has a structure with empty lattice points. However, the term »solid solution» is so familiar, and no alternative nomenclature is yet available for the second phenomenon outlined above, hence the use of the term in the two senses. A number of examples of this second phenomenon were discussed by Strock (102), and he refers to them as crystal structures with defect lattices.

Before passing to the investigation itself, I should like to express here my gratitude to my friends and associates for the assistance and advice I have received from them. It is not possible to name them all here. However, first and foremost I am indebted to Professor Percy Quensel for the hospitality I have enjoyed in the Mineralogical Institute since I arrived here by accident of war nearly three years ago. An enjoyable excursion to Långban in his company led to this research, and his advice and suggestions have always been freely given me. Much of the results of this research are due to the use of X-ray methods and synthetic preparations; this part of the work was carried out in the Institute of Inorganic Chemistry, and my especial thanks are due to Professor Arne Westgren and to the staff of that institute, in particular Mr Anders Byström and Mr Sven Sahlquist, for their instruction and assistance in making and interpreting the large number of X-ray photographs taken during this and previous investigations. Discussions with Professor Westgren and Docent Phragmén have led to a clearer appreciation of the physicochemical problems involved in this investigation. My knowledge of ore-microscopical methods is entirely due to the careful instruction I have received from Dr. Olof Ödman, whose time and experience were constantly at my disposal for this purpose. I would also express my thanks to Professor N. H. Magnusson for many fruitful discussions on problems of mineral paragenesis in general, and on the origin of the Swedish iron and manganese ores, especially Långban, in particular. Not least would I acknowledge my indebtedness to Miss Anne-Marie Sjögren, assistant in the Mineralogical Institute, for much help; all the figures in this paper were drawn by her, and she has also done much secretarial work on the manuscript itself.

Although most of the material investigated came from the collections of the Mineralogical Institute, many exceedingly useful specimens came from outside sources. Thanks to the willing cooperation of Professor G. Aminoff and Dr. N. Zenzén the collections of the Swedish Riksmuseum were always available to me; the Mineralogical Institute has also received much valuable material of foreign manganese ores from Professor P. Ramdohr and Professor H. Schneiderhöhn, which was at my disposal for investigation, and which contributed largely to the completeness of the investigation.

Acknowledgement is also made in the text to a number of people who have helped me in particular ways.

Finally this would not be complete if I did not mention the many kindnesses, not only in scientific matters, which have contributed to make my enforced stay in Sweden such a memorable one.

## The iron oxides.

### FeO — Wüstite.

In discussing ferrous oxide it must first be emphasised that a stable solid phase with composition corresponding to the formula FeO does not exist.

This was first discovered by R. Schenck and Dingmann (89) in 1927, who showed that the so-called FeO always contains less iron than this formula requires; their results indicated that the existence range of the homogenous phase that had previously been considered as FeO was from 75.76 % to 76.59 % Fe at 600° and widened with increasing temperature, being from 75.22 % to 77.33 % Fe at 1100° (for pure FeO Fe = 77.73 %). They named this homogeneous phase wüstite, and this name has established itself in metallurgical literature. More recent work has largely confirmed the results of Schenck and Dingmann, differing only in the extent rather than in the position of the wüstite field (Fig. 1). The most thorough and satisfactory investigation of the wüstite solid solutions is that of Jette and Foote (46, 47), who fixed the homogeneity imits of this phase by means of X-ray studies and gave an adequate explanation of its structure. According to their results wüstite has the NaCl type of lattice common to a large group of compounds of the RO type, i. e. the same structure as Wyckoff and Crittenden (127) had determined for the compound which they believed to be pure FeO, but which was actually wüstite. Jette and Foote found that the lattice dimensions of the wüstite solid solutions decrease rapidly with decrease n iron content, and came to the conclusion that the form of substitution of iron by oxygen in the theoretical FeO to give wüstite was complex, consisting in the replacement of an FeO group by oxygen. Their results on the homogeneity limits of wüstite will be discussed later, under the system $FeO-Fe_2O_3$.

Thus the observations that have been published as purporting to refer to FeO in reality refer to this wüstite phase. In addition, however, by far the greater part of the methods used for the preparation of ferrous oxide can be dismissed as not only valueless but also misleading,

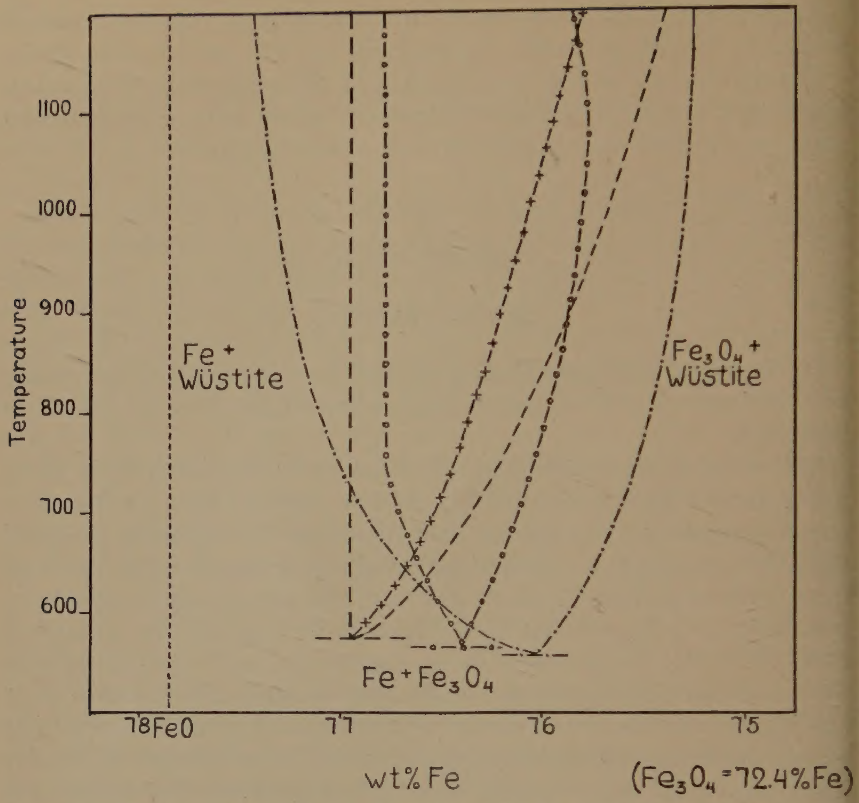


Figure 1. The homogeneity limits of wüstite, according to different investigators.
—•—•—• R. Schenk & Dingmann (89); — — — — Pfeil (81);
—×—×—× Vogel & Martin (110); —∘—∘—∘ Jette & Foote (47).

the supposed ferrous oxide having generally been metallic iron, $Fe_3O_4$, or mixtures of these with or without carbon. The preparation of a homogeneous wüstite is troublesome, the most satisfactory method being the reduction of $Fe_3O_4$ or $Fe_2O_3$ with metallic iron, or the controlled oxidation of metallic iron by heating in air. The material sold commercially as ferrous oxide is $Fe_3O_4$, with or without admixed iron; this can readily be established by testing with a magnet, since wüstite is non-magnetic.

According to Jette and Foote, the lattice dimensions of wüstite vary from 4.2722 A for a product containing 75.72 wt.% Fe to 4.3023 A for a product with 76.79 wt.% Fe (accuracy about ± 0.001 A). By extrapolation of their measurements they gave the lattice dimensions for the theoretical FeO as 4.332 A. The values given by other investigators for the lattice dimensions of FeO — 4.27 to 4.30 A — all refer to wüstite.

Pure wüstite is brittle black solid, and, as mentioned previously, non-magnetic. It is practically insoluble in sulphuric acid and only slowly soluble in boiling hydrochloric acid. Polished sections are unaffected by the usual etching agents. The density, as measured by Jette and Foote, varies from 5.61 to 5.73. The figure 1370° is often given as the melting point of wüstite, but this is probably too low, on account of the presence of impurities, and according to Jette and Foote it does not begin to melt till over 1400°.

Wüstite is unstable at ordinary temperatures, the reaction

$$4FeO \rightleftarrows Fe_3O_4 + Fe$$

proceeding to the right below 575° and to the left above this temperature. Thus the triple point at which iron, wüstite, and magnetite are in equilibrium lies at 575°. By rapid cooling wüstite can be obtained at room temperatures, at which the rate of disintegration into $Fe_3O_4$ and Fe is practically zero. Sufficiently slow cooling, however, results in the complete disintegration of wüstite.

The occurrence of FeO, or rather wüstite, as a mineral has only once been indicated, by Brun in 1924 (10), who named it iozite. His description is far from convincing, and has never been confirmed. According to him iozite often occurs in recent, iron-rich lavas, as swarms of minute granules up to 0.01 mm. in diameter surrounding microlites of felspar and pyroxene. However, the properties of iozite, especially its strong ferromagnetism, are not those of wüstite, but of magnetite, and it appears very probable that Brun's iozite is actually magnetite, possibly with excess FeO in solid solution. The analyses on which Brun based his arguments for the presence of a mineral corresponding to FeO in his lavas were analyses made on the rock as a whole; he did not attempt to isolate his iozite in any way. He also believed that FeO and $H_2O$ cannot exist together at the temperature of solidification of a basic lava, and argued that the occurrence of iozite proved his contention that magmas must be »dry». Even this argument is erroneous, as is proved by the experimental results on the reaction

$$Fe_3O_4 + H_2 \rightleftarrows 3FeO + H_2O.$$

It has been shown (Tigerschiöld, 104) that at 1100° (the approximate temperature of basaltic magma) the equilibrium in this reaction lies to the right, the ratio $H_2O/H_2$ being about 20/1. Wüstite is therefore quite stable in the presence of water vapour at this temperature.

Brun's arguments are faulty and the evidence he presented for the occurrence of FeO (or rather wüstite) as a mineral is negligible. However, the faultiness of his arguments does not necessarily deny the possibility of wüstite occurring as a result of natural processes. Shepherd (96) has shown that the gases from the basaltic magma at Kilauea consist largely of $H_2O$, $CO_2$, $N_2$, $SO_2$, $CO$, and $H_2$. Thus in the magma the following reactions will be of great importance:

$$Fe_3O_4 + H_2 \rightleftarrows 3FeO + H_2O$$
$$Fe_3O_4 + CO \rightleftarrows 3FeO + CO_2$$

At high temperatures equilibrium in these reactions lies so far to the right that the presence of $H_2$ or CO even in small concentration is sufficient to reduce the higher oxides of iron to FeO. It is therefore probable that in a basaltic magma the greater part of the iron is in the ferrous state. Usually, of course, the ferrous iron present is combined as silicate, but in iron-rich basalts it may be possible for a wüstite phase to be formed, especially in rocks low in titanium, which when present combines with the FeO. Wüstite, in solid solution with other monoxides, is known as a slag phase. However, the proof of the presence of such a phase in lavas requires a very different technique than that employed by Brun. To successfully show the presence or absence of such a phase requires the separation of a heavy fraction from the powdered lava and its examination by powder photographs to establish the phases present, and by chemical analysis to establish their composition. For the present it may safely be said that wüstite is not known to occur as a mineral.

## $Fe_3O_4$ — Magnetite

Many oxides have been described with formulas between FeO and $Fe_2O_3$, but the only homogeneous phase is $Fe_3O_4$, known under the name magnetite, which has come to mean not only the natural mineral, but is quite generally understood to include the artificially prepared $Fe_3O_4$ also. There is little reliable evidence for the occurrence of polymorphic forms of $Fe_3O_4$, although there are some strange discontinuities in several curves with which energy is associated which require further investigation. Schlaepfer and Niggli (91), in experiments on mineral synthesis; obtained some orthorhombic crystals which they thought were probably an unstable chrysoberyl modification of $Fe_3O_4$. However, it was in no way shown that the composition of these crystals was actually $Fe_3O_4$, and no further evidence for a chrysoberyl modification has been published.

It may therefore be said that only one form of $Fe_3O_4$ is known to exist. This form is cubic, a member of the spinel group. Its crystal structure was one of the first to be investigated, being analysed independently in 1915 by Bragg in England and Nishikawa in Japan. Since then many workers have studied the structure of magnetite. The cubic cell contains 8 $Fe_3O_4$ molecules; measurements of the length of the cube edge vary from 8.36 A to 8.42 A, the best value being 8.38 A.

Many elements may substitute either the divalent or trivalent atoms in $Fe_3O_4$, and as a result pure magnetite is the exception and not the rule. It is astonishing to see the variation in the qualitative and quantitative data on the physical properties of magnetite; this variation is certainly only partly due to varying composition, inhomogenity of material and inadequate technique having had an important influence. Thus figures for the specific gravity vary between 4.9 and 5.3, if the obviously erroneous values are excluded; from the X-ray data the true specific gravity of $Fe_3O_4$ must be close to 5.20.

Many determinations have been made of the melting point of $Fe_3O_4$, but they are generally too low on account of the presence of impurities. The latest, and apparently the most reliable value is that of Greig and his co-workers at the Geophysical Laboratory (32). They state that magnetite, corresponding to the formula $Fe_3O_4$, melts to a liquid of the same composition at 1591° ± 5° under a small but unknown pressure of oxygen. An increase in the oxygen pressure, with consequent increase in the oxygen content of the magnetite, is accompanied by a decrease in the temperature of melting; at constant pressure oxygen is taken up in the process.

The most noteworthy, and at the same time perhaps the least understood property of $Fe_3O_4$ is its ferromagnetism. The characteristics of this ferromagnetism are well known, but a completely satisfactory and explanatory theory is still lacking. Magnetite loses its magnetism at high temperatures, the change from ferromagnetic to paramagnetic taking place at about 590°, the so-called Curie point. This change is not accompanied by any structural alteration. Acording to Hilpert and his co-workers (42) the magnetism of $Fe_3O_4$ is connected with its chemical nature as a ferrous ferrite; they have synthesised many ferrites of different metals and have shown that all are ferromagnetic; apparent exceptions, such as the alkali ferrites, which are paramagnetic at ordinary temperatures, become ferromagnetic at low temperatures, their Curie points being below zero Centigrade. Hilpert therefore concludes that the ferromagnetic properties of magnetite and the ferrites depend upon the presence of $Fe_2O_3$ acting as an acid. The magnetism of magnetite is certainly not directly dependent on its cubic symmetry, since other ferrites have lower symmetry, being tetragonal and hexagonal. Hilpert's explanation is satisfactory up to a point, but it fails to explain ferromagnetism in its entirety, since many other substances besides ferrites are ferromagnetic. Attempts have been made to derive the conditions for the occurrence of ferromagnetism on purely theoretical grounds, by the methods of quantum mechanics; in particular the theory of Heisenberg (38) has been much accepted, but although it can account for the ferromagnetism of iron and the related metals it does not appear to be fully applicable to compounds with other elements. It is not yet possible to state all the conditions which must be fulfilled in order that ferromagnetism will appear. Chemical composition, atomic proportions, and lattice structure perhaps all play a part, but the determining factor is probably the distribution of the electrons within the molecule.

Since $Fe_3O_4$ is one of the most stable oxides of iron, magnetite occurs in many terrestrial rocks and also in meteorites, being formed under a wide variety of circumstances. In general its presence is indicative of a high temperature of formation, although it is by no means absent from low-temperature deposits. The natural forms are rarely or never hydrated, although hydrates with one and with one and one-half molecules of water have been prepared in the laboratory. The mutual relations between hematite and magnetite are of the greatest importance in the study of ore-deposits, but this question will be discussed later in the consideration of the system $Fe_2O_3$-$Fe_3O_4$.

## $Fe_2O_3$ — Maghemite and Hematite.

Many varieties of $Fe_2O_3$ have been described, but only two distinct forms are definitely known. These are $\alpha$-$Fe_2O_3$, which occurs in nature as the mineral hematite, and $\gamma$-$Fe_2O_3$, which also occurs as a mineral, if much more rarely than hematite, and has been known under a variety of names, of which maghemite is the one generally accepted.

The occurrence of two forms of $Fe_2O_3$ is an instance of the general phenomenon of polymorphism. Polymorphism is of two types, enantiotropy and monotropy. Enantiotropy is characterised by two polymorphic forms being in equilibrium with each other at a definite and (at constant pressure) fixed temperature known as the transition point; one form is stable at temperatures above the transition point, the other at temperatures below this point; the transition from the form stable at temperatures below the transition point to the form stable above this point is accompanied by absorption of heat. Monotropy, on the other hand, is characterised by there being no transition point between the two forms; under all conditions where both can exist the one form is always stable, the other always metastable. The transition from the metastable form to the stable form is accompanied by a decrease in free energy. Generally the specific gravity of the metastable form is less than that of the stable form. The characteristic distinction between enantiotropy and monotropy is that for enantiotropic forms the transition from one form to the other is reversible, whereas for monotropic forms the change is irreversible, being always from metastable form to stable form, and never vice versa.

It is evident, on going through the literature, that the significance of the relations between the two forms of $Fe_2O_3$, whether enantiotropic or monotropic, has not been fully appreciated. However, a consideration of the evidence shows that $\gamma$-$Fe_2O_3$ is a metastable form, and $\alpha$-$Fe_2O_3$ the stable form. Many investigators have given a transition point for the change from $\gamma$-$Fe_2O_3$ to $\alpha$-$Fe_2O_3$, but the temperature of this supposed transition point has varied widely, from a little over 200° to 700° and even 800°. The supposed transition point has merely been the temperature at which the rate of change has become noticeable, and this temperature is largely dependent on the previous history of the sample, its method of preparation, and the presence or absence of impurities. The presence of small amounts of foreign substances may either stabilize the metastable $\gamma$-$Fe_2O_3$ or accelerate its change to the $\alpha$-form. The change from $\gamma$-$Fe_2O_3$ to $\alpha$-$Fe_2O_3$ is accompanied by evolution of heat, a phenomenon noticed already by Berzelius in 1820 (7, p. 54), although the nature of the change was not then understood. Berzelius remarked that $Fe_2O_3$, prepared by the dehydration of the precipitated oxide, when heated showed calorescence or heat evolution, and that after calorescence the oxide was less attacked by acids, and less reactive chemically, but that the change was not accompanied by any change of weight. This calorescence has been described many times since, and various explanations have been put forward for it, but the true nature of the change is that it is the irreversible transition from $\gamma$-$Fe_2O_3$ to $\alpha$-$Fe_2O_3$. Mixter (64) considered that this change was a polymerization, and from thermochemical measurements evaluated the evolution of heat accompanying the change to 9000 calories per mol, which he called the heat of polymerisation. Confirmation of this figure is given in a recent paper by Fricke and Zerrweck (27), who state that under comparable conditions the heat content of $\gamma$-$Fe_2O_3$ is at least 6000 calories greater than that of $\alpha$-$Fe_2O_3$.

The lack of agreement between the temperatures given by different investigators for the transition $\gamma$-$Fe_2O_3$ to $\alpha$-$Fe_2O_3$ already suggests that the two forms are not enantiotropic, but monotropic, and this is confirmed by the irreversibility of the process. Iimori (43) is the only person who has claimed to have observed a reversible transition from $\gamma$-$Fe_2O_3$ to $\alpha$-$Fe_2O_3$. He studied the oxide film formed on iron at different temperatures by the method of electron diffraction, and states that there is a reversible transition at 330°. However, if this oxide film was heated above 350° he was unable to reverse this process. His description is hardly convincing, especially in the face of all other investigations which have not observed any such temperature of reversible transition.

On the grounds of the irreversibility of the process and the impossibility of preparing $\gamma$-$Fe_2O_3$ from $\alpha$-$Fe_2O_3$ directly one would be justified in considering the two forms as monotropic. Combined with the fact that $\gamma$-$Fe_2O_3$ changes to $\alpha$-$Fe_2O_3$ with evolution of heat and that the density of the $\gamma$-form is considerably less than that of the $\alpha$-form the evidence for the metastable nature of the $\gamma$-form is conclusive. Thus at all temperatures $\alpha$-$Fe_2O_3$ is the only stable form of ferric oxide. However, at ordinary temperatures the rate of inversion of $\gamma$-$Fe_2O_3$ is so vanishingly slow that it can easily be prepared and studied and can even occur as a mineral — maghemite.

$\gamma$-$Fe_2O_3$ has had a chequered history, having been observed, described, forgotten, and rediscovered several times over. Its existence has been doubted, since its most characteristic difference from $\alpha$-$Fe_2O_3$, the strong ferromagnetism, has been ascribed by sceptics to the presence of ferrous iron in the form of magnetite. As mentioned above, Berzelius had observed the evolution of heat when $\gamma$-$Fe_2O_3$ inverts to the $\alpha$-form, although he did not realize the nature of the process. In 1838 von Kobell (112) recorded the fact that the mineral now known as lepidocrocite[1] became magnetic on heating. In 1848 Plücker (82) prepared a ferromagnetic iron oxide, evidently $\gamma$-$Fe_2O_3$, by heating an artificially prepared ferric hydrate — Plücker's measurements showed that its magnetism was 15204 against 40227 for $Fe_3O_4$ and 533 for hematite from Elba. The existence of a ferromagnetic ferric oxide, quite free from ferrous iron, was first proved by Robbins in 1859 (85), who prepared it by the oxidation of $Fe_3O_4$. This discovery was later made independently by Malaguti in France (56), who determined the density of the ferromagnetic form as 4.686, whereas the density of the usual form of $Fe_2O_3$ was 5.144 — values in good agreement with those accepted at the present day. The occurrence of a ferromagnetic ferric oxide was observed by later investigators — thus Liversidge (54) noted that iron rust often consisted largely of this substance, and that its specific gravity was much lower than that of hematite or magnetite, and Hilpert (41) again showed that the ferromagnetic oxide prepared by the oxidation of $Fe_3O_4$ and $Fe(OH)_2$ did not contain ferrous iron. However, it was not until 1925, when Sosman and Posnjak published the results of their investigations (101), that the true nature of ferromagnetic ferric oxide as a polymorphic form of $Fe_2O_3$ was finally established. They described various ways of preparing $\gamma$-$Fe_2O_3$ (independently rediscovering its formation by the heating of lepidocrocite) and were the first to record its occurrence as a mineral, in a specimen from a gossan deposit at Iron Mountain, Shasta County, California. They studied its physical properties, and, most important of all, showed by powder photographs that its structure must be practically identical with that of magnetite, and thus that it was quite distinct from $\alpha$-$Fe_2O_3$, hematite. Since the publication of Sosman and Posnjak's paper, $\gamma$-$Fe_2O_3$ has been the subject of intensive investigation, and the literature on it is now large.

---

[1] There has been considerable confusion in the nomenclature of the ferric oxide hydrates, the mineral here referred to as lepidocrocite being more correctly goethite in the original sense of this name. However, I here follow the usual practice, using the name lepidocrocite for the mineral corresponding to the artificial $\gamma$-FeOOH (Ger. Rubinglimmer), goethite for $\alpha$-FeOOH (Ger. Nadeleisenerz).

It has been found that $\gamma$-$Fe_2O_3$ can be prepared in many ways. It is obtained when $Fe_3O_4$ or $Fe(OH)_2$ is oxidized under suitable conditions, either by heating in air or oxygen or when treated with oxidizing agents; by the decomposition on heating of certain iron salts, and, as mentioned above, by the heating of lepidocrocite or artificial $\gamma$-FeOOH (goethite, $\alpha$-FeOOH, when heated is converted directly to $\alpha$-$Fe_2O_3$); and by burning $Fe(CO)_5$. It is also formed in the iron arc, and Caglioti and D'Agostino have shown that $Fe_2O_3$ aerogel consists of $\gamma$-$Fe_2O_3$ (12). Michel (61) found that it was formed by the decomposition of unstable ferrites. The primary oxide film on heated iron is said to be $\gamma$-$Fe_2O_3$ (Miley, 62). As the previous discussion showed, it is impossible to prepare it directly from $\alpha$-$Fe_2O_3$. For some experiments in connection with this investigation it was prepared by precipitating a hot strong solution of $FeSO_4$ with a slight excess of NaOH, washing the precipitate with hot water until free from sulphate, and heating it in a drying oven with free access of air at 165° for 24 hours. The product was a yellow brown powder, strongly magnetic; powder photographs confirmed that it was $\gamma$-$Fe_2O_3$, the cell edge being 8.325 A.

As soon as it was realized that $\gamma$-$Fe_2O_3$ has a structure very similar to that of magnetite attempts were made to find out the positions of the atoms in the unit cell. Since the X-ray diffraction patterns of magnetite and $\gamma$-$Fe_2O_3$ are practically identical it was thought that the problem consisted of fitting in four extra oxygen atoms in the magnetite unit, according to the scheme:

unit cell $Fe_3O_4$: $Fe_{24}O_{32} + 4O \rightarrow Fe_{24}O_{36}$ : unit cell $\gamma$-$Fe_2O_3$.

On this assumption Welo and Baudisch (121), Twenhofel (105), and Thewlis (103) proposed structures in which the four extra atoms were accomodated. However, there are strong objections to such a structure; firstly it is difficult to see how four extra oxygen ions, with their large radius, could be fitted into the already close-packed structure of magnetite; secondly it gives rise to the improbable coordination number 5; and thirdly the density of $\gamma$-$Fe_2O_3$, instead of being less, should actually be greater than that of $\alpha$-$Fe_2O_3$. A structure of $\gamma$-$Fe_2O_3$ free from these objections was published independently and almost simultaneously from three sources in 1935: by Hägg (35), Verwey (107), and Kordes (50). All came to the same conclusion: the excess oxygen in the spinel lattice of $\gamma$-$Fe_2O_3$ compared to $Fe_3O_4$ is due to empty Fe positions, $^1/_9$ of the metal positions in the magnetite lattice being vacant in $\gamma$-$Fe_2O_3$. Thus the unit cell content of $\gamma$-$Fe_2O_3$ is not $Fe_{24}O_{36}$, but $Fe_{21\,1/3}\ O_{32}$. Hägg showed that the oxidation of $Fe_3O_4$ to $\gamma$-$Fe_2O_3$ is a continuous process, the cell edge decreasing continuously from 8.380 A for $Fe_3O_4$ to 8.322 A for $\gamma$-$Fe_2O_3$, the measured density decreasing at the same time from 4.78 to 4.59. The calculated density for $\gamma$-$Fe_2O_3$ from the X-ray measurements is 4.88, that of $Fe_3O_4$ 5.20. The structure proposed by Hägg, Verwey, and Kordes is in good accord with both X-ray and physical data and is undoubtedly correct in principle, although recently Haul and Schoon (36) have observed a number of weak additional reflections in powder photographs of $\gamma$-$Fe_2O_3$, which they suggest indicate either a lower symmetry or a larger unit cell than has been adopted for this substance. A possible explanation is also that the vacant positions are regularly arranged in the lattice.

In the last fifteen years the chemical and physical properties of $\gamma$-$Fe_2O_3$ have been intensively studied, and an immense mass of information has been collected. Most important from a mineralogical point of view is undoubtedly its temperature of formation and the temperature at which it changes irreversibly to $\alpha$-$Fe_2O_3$, i. e. its region of relative stability. On these points, however, the published observations differ greatly and are often mutually contradictory. Most of the mutual contradiction is due to lack of appreciation of the monotropic character of $\gamma$-$Fe_2O_3$ — instead of having a fixed stability field it is unstable under all conditions, but its relative instability can be powerfully influenced by the method of formation, the past history of the specimen, and the presence or absence of impurities. Thus Welo and Baudisch (122) found that $\gamma$-$Fe_2O_3$ is unstable at 285°, inverting in two hours to the $\alpha$-form, and state that the inversion takes place slowly at 250° and extremely slowly at 200°, but can still be detected. Sachse and Haase (88) found that ageing has a profound effect on the inversion, a preparation of

$\gamma$-$Fe_2O_3$ which had been kept for four years having much weaker magnetism than the freshly prepared substance, indicating that it can invert slowly at ordinary temperatures; on heating, the aged material inverted much more rapidly at a given temperature than the freshly prepared substance. The inversion thus appears to be autocatalytic. For an individual preparation the speed of inversion increases with the temperature, but observations on the half-life period of one specimen at a certain temperature cannot be used to calculate the half-life period of any other specimen. The presence of foreign substances has an enormous effect on the stability of $\gamma$-$Fe_2O_3$. Thus Michel (61) found that $\gamma$-$Fe_2O_3$ can be heated to temperatures above 700° without inverting to the $\alpha$-form, if it is stabilized by the presence of small amounts of basic oxides, such as BeO, MgO, NaOH, and KOH. He was able to measure the Curie points of these stabilized preparations, and by extrapolation to find that the Curie point for pure $\gamma$-$Fe_2O_3$ lies at 675°. This determination of the Curie point of $\gamma$-$Fe_2O_3$ is of great interest for the discussion of the magnetic properties of $\alpha$-$Fe_2O_3$ (p. 118).

Since $\gamma$-$Fe_2O_3$ has a much lower specific gravity than $\alpha$-$Fe_2O_3$ it is to be expected, from Le Chatelier's principle, that pressure would promote the formation of $\alpha$-$Fe_2O_3$. This has been confirmed experimentally in an interesting way by Baudisch (4). He heated two samples of $\gamma$-FeOOH under the same conditions at 240°, one sample in an open pyrex tube, the other in a sealed pyrex tube. The product in the open tube was $\gamma$-$Fe_2O_3$, the product in the sealed tube $\alpha$-$Fe_2O_3$. The pressure of the water vapour produced by dissociation of the FeOOH was sufficient to cause the formation of the $\alpha$-form in the sealed tube. In the same paper Baudisch gives a summary of the contrasted properties of $\alpha$-$Fe_2O_3$ and $\gamma$-$Fe_2O_3$. The differences are great, both chemically and biologically, $\gamma$-$Fe_2O_3$ being much more reactive. In particular, $\gamma$-$Fe_2O_3$ shows remarkable catalytic effects, especially in oxidation-reduction reactions.

Turning now to the mineralogical aspects, the occurrence of $\gamma$-$Fe_2O_3$ as a mineral was first mentioned by Sosman in 1917 in an address to the Chemical Society of Washington (100), but a full description of this discovery (with analysis) was first published in Sosman and Posnjak's paper on ferromagnetic ferric oxide in 1925 (101). They were fully aware that they were dealing with a new mineral species, but as their material was not very pure, containing only 85.3 % $Fe_2O_3$, they refrained from naming it, in the expectation that more and better material would be forthcoming from other localities. They had not long to wait; in 1927 Wagner, in a letter to Economic Geology, announced the discovery of very large quantities of this substance in the so-called titaniferous magnetite segregations in the upper part of the norite zone of the

Bushveld Igneous Complex in the Transvaal, and proposed the name maghemite for the mineral (113). In the following year, in a publication on the iron ores of South Africa, he gave a more detailed description, with chemical analyses, of the Bushveld maghemite (114). He sent specimens to Schneiderhöhn, who confirmed the identity of maghemite, and also pointed out the presence of intimately intermixed ilmenite, both as irregular grains and as minute oriented lamellae. The maghemite was the product of the alteration of magnetite, the original material having been an unmixed titanomagnetite. The chemical analyses of the Bushveld maghemite all showed a considerable content of $FeTiO_3$, due to the ilmenite inclusions.

Later Walker (115) investigated a specimen of maghemite from Bon Accord, Transvaal (also in the Bushveld complex), and had a new analysis made. This analysis was similar to those published by Wagner, and also showed the presence of a considerable quantity of titanium. Although the analysis could be satisfactorily interpreted on the assumption that the analysed material was a mixture of $Fe_2O_3$ and ilmenite, Walker assumed, without giving any acceptable reason for this assumption, that the titanium was present as $Ti_2O_3$ in solid solution with $Fe_2O_3$. Apparently he was strengthened in this belief by the examination of a polished section of his material by Professor Thomson, who reported that 95 % of the opaque material, apart from limonite, was made up of a single mineral which was definitely anisotropic. On these grounds Walker gave the formula for this mineral as $(Fe, Ti)_2O_3$ and suggested that Wagner's name maghemite should be applied to a substance of this composition rather than to ferromagnetic ferric oxide, $\gamma$-$Fe_2O_3$.

It is difficult to understand Walker's presentation, and especially the microscopical report of Professor Thomson. I have examined polished sections of specimens from the same locality as Walker's material in the collections of this institute, and can in no way confirm Professor Thomson's results. The results of this examination agree fully with those of Schneiderhöhn published by Wagner, namely that the mass of the specimens consists of an isotropic mineral — maghemite — in which occur irregular grains and minute oriented lamellae of ilmenite. The lamellae of ilmenite are so small that they are very easily overlooked, and Thomson may well have done so, but according to my observations the maghemite is in no way anisotropic. The amount of ilmenite in the polished sections would account for the titanium in Walker's analysis, although I do not wish to deny the possibility of at least a part of the titanium being present in solid solution in the maghemite. However, the determining factor is that this maghemite gives a powder photograph quite identical with that of artificial $\gamma$-$Fe_2O_3$, with a cell edge of 8.32 A. There is thus no doubt that Wagner's maghemite is identical with $\gamma$-$Fe_2O_3$, and Walker's proposal to transfer Wagner's name from naturally occurring ferromagnetic ferric oxide to a hypothetical $(Fe, Ti)_2O_3$ is inadmissable, quite apart from consideration of the laws of nomenclature.

Maghemite has now become accepted as the name for the naturally occurring $\gamma$-$Fe_2O_3$, but not without opposition. Schneiderhöhn and Ramdohr, who thoroughly discussed this mineral in their »Lehrbuch der Erzmikroskopie», considered maghemite an unsuitable name on the grounds that it suggested a magnetic hematite, and would have preferred to call it sosmanite, but bowed to the laws of priority and adopted the name maghemite. Not so Winchell, however (125); he rejected maghemite as either indicating a substance between magnetite and hematite (homogeneous substances of this kind are unknown!) or hematite which had become magnetic, and instead would call it oxymagnite, an abbreviation for »oxydized magnetite». Apart altogether from the fact that Wagner clearly stated that name maghemite was intended for the naturally occurring $\gamma$-$Fe_2O_3$ and that it would be a gross and unnecessary breach of priority to rename it oxymagnite, Winchell's name can be justifiably rejected on the grounds that natural $\gamma$-$Fe_2O_3$ can be formed not only by the oxidation of magnetite, but also by the dehydration of lepidocrocite.

A considerable literature has grown up during the past few years on the occurrence and properties of maghemite. The most recent general paper is that by Newhouse and Glass published in 1936 (70). These investigators published several new analyses of maghemite from different localities, and from powder photographs showed that maghemite has a cell edge close to that of artificial $\gamma$-$Fe_2O_3$ (8.32 A), and distinctly lower than that of magnetite (8.38 A). Newhouse and Glass come to the curious conclusion that the ferromagnetic ferric oxide originally described by Sosman and Posnjak (101) from Iron Mountain, California, is not identical with maghemite, although it is undoubtedly naturally occurring $\gamma$-$Fe_2O_3$, with a cell edge of 8.30 A. The reason for this decision seems to rest on a certain difference in colour and hardness of the Iron Mountain material as compared with maghemite from other localities, differences insufficient to outweigh the evidence from X-ray and chemical investigations.

The analyses that have been published of maghemite all show $Fe_2O_3$ as the principal component. FeO is often present; often, especially in specimens from the Bushveld occurrences, it is probably combined with the $TiO_2$ present as ilmenite; it may also be present as remnants of magnetite, but it is possible that in some cases it is present in the homogeneous $\gamma$-$Fe_2O_3$, as the oxidation of $Fe_3O_4$, as Hägg (35) has shown, is a continuous process. It is therefore conceivable that all stages in the oxidation of magnetite to maghemite may occur, and therefore that the optical properties as seen in polished section would also vary continuously from magnetite to maghemite. So far such intermediate substances have not been certainly recognized; identification would probably be difficult, although measurement of the cell dimensions would be a reliable method, as the length of the cell edge decreases considerably from magnetite to maghemite. The X-ray measurements should be supplemented by chemical analysis, as the cell dimensions of magnetite can also be lowered by the presence of other elements replacing iron, although most replacement in magnetite — by manganese, zinc, titanium, — results in an increase in the size of the unit cell, and replacement by magnesium has little effect, since the cell edge of $MgFe_2O_4$ is about 8.36 A, within 0.02 A of that of pure magnetite. This possibility of the occurrence of partly oxidized magnetite may account for some of the contradictory statements as to the appearance of magnetite in polished sections.

As well as the FeO shown in analyses of maghemite, $TiO_2$ is also often present, usually in combination as ilmenite, but it is possible that titanium in solid solution in magnetite may remain in solid solution under the oxidation to maghemite, and thus be present in homogeneous maghemite. Apart from the Bushveld occurrences, however, the titanium content in analyses of maghemite is generally rather low. Some analyses also show small amounts of MgO and $Al_2O_3$, and $H_2O$ is often present up to 3 % or more. As maghemite is usually a product of supergene processes and is nearly always accompanied by limonite (limonite is here used in the sense of ferric oxide hydrates without attempting to distinguish between goethite, lepidocrocite, and amorphous substances) the water may be adsorbed or combined in the limonite.

Of the different physical properties of maghemite, the specific gravity is one of the most distinctive, being much lower than that of the other oxides of iron. The specific gravity calculated from the cell dimensions is 4.88, against 5.20 for magnetite and 5.25 for hematite. Maghemite is often rather mixed with foreign material, and as a result the recorded specific gravity varies considerably. The following figures are representative: From Bushveld, 4.41, 4.50 (Wagner, 114), 4.70 (Walker, 115); Alameda County, California, 4.62 (Walker, 116). The identification of maghemite in polished sections is fully discussed by Schneiderhöhn and Ramdohr (93).

An interesting sidelight on maghemite is the discovery that lodestone (in the sense of a naturally occurring polar-magnetic substance) often consists largely of this mineral.[1] This was first pointed out by Newhouse (68) in 1929 (although his description of the appearance of the mineral in polished sections is difficult to understand when compared with later observations). Two years later Walker (116) went into the occurrence of polarmagnetic iron oxides more deeply, and from the analyses of eight specimens of lodestone was able to draw the conclusion that lodestones contain a considerable excess of $Fe_2O_3$ over the formula of magnetite, and that the strongest lodestones show the greatest excess. Lodestones also showed a lower specific gravity than magnetite. Walker concluded that as the strongest lodestones contain the greatest excess of ferric oxide it was probable that this excess is present in the form of ferromagnetic ferric oxide, and that the polarity is a function of the percentage of this substance. Although this conclusion may not be perfectly general, it is certainly true that many specimens of maghemite from different localities show strong polar-magnetism.

Maghemite has now been recorded from a number of localities, and it is possible that it is not uncommon, but is often wrongly identified as magnetite or hematite. Search of the literature gives the following occurrences: Iron Mountain, Shasta County, California, in a gossan deposit (Sosman and Posnjak, 101); in the upper part of the norite zone in the Bushveld Igneous Complex, Transvaal, replacing magnetite (Wagner, 113); from Durant, Oklahoma, an iron ochre of unknown origin (Shannon, 95); »Martite» from Cerro Mercado, Durango, Mexico (Shannon, 95); Alameda County, California, replacing magnetite (Newhouse and Glass, 70); Windpass Mine, British Columbia, replacing magnetite (Newhouse and Glass, 70); Magnet Cove, Arkansas, replacing magnetite (Newhouse and Glass, 70); replacing magnetite in lavas from the following localities: in weathered shonkinite, Katzenbuckel (Schneiderhöhn and Ramdohr, 93); in nepheline and melilite-bearing lavas, Mt. Elgon, British East Africa (Ödman, 72); in anorthoclase trachyte from Arfertuarsuk Fjord, West Greenland (Nieland, 71); in basalt from Katzenbuckel (Nieland, 71); and in trachyte from various localities (Newhouse, 69). Frebold and Heseman (26) claimed to have observed maghemite in the Devonian iron ores from the Harz and Siegerland, but, as Schneiderhöhn and Ramdohr pointed out, their description is so obscure, and their observations, both as to physical properties and paragenesis, differ so greatly from those of genuine maghemite that this occurrence cannot be accepted.

On going through some of the older literature on the natural occurrence of the different iron oxides I have noticed a number of instances where maghemite was evidently met with. Thus in 1902 Rinne (84) wrote a short paper on a »Magneteisenerz» which he had observed on the island of Luzon in the Philippines; it was polarmagnetic, and evidently a weathering product. Rinne called it magnetite because of its magnetic properties, no analysis being made. A very similar occurrence was described from Surinam (Dutch Guiana) by Voit (111); this was a lateritic iron ore which often contained magnetic material, supposed by Voit to be magnetite, although all his analyses show only $Fe_2O_3$. Kosmann (51) discovered a limonitic iron ore near Frankenstein in Silesia which was strongly magnetic, and at first suspected that the magnetism was due to the presence of ferrous iron, but then had the material analysed and found no trace of FeO. He was convinced that the magnetism must be due to a peculiar molecular grouping, but did not pursue the investigation further. A magnetic iron oxide which was evidently maghemite was recorded by Merrill in 1902 as a weathering product on the Admire meteorite found in Lyon County, Kansas (60). His description is interesting in that he was evidently the first to observe the appearance of maghemite in polished sections; he writes: »The first product of the oxidation of the iron is not limonite, but a highly lustrous — on polished surfaces, blue — material which crushes down readily to a fine brown magnetic powder». It is probable that maghemite will be found to be relatively common as the product of weathering of meteoric and terrestrial irons, as the rusting of iron and steel often results in the formation of $\gamma$-$Fe_2O_3$, as was first pointed out by Liversidge (54).[1]

---

[1] Many occurrences of lodestone have apparently been called magnetite merely on account of their magnetic properties, not having been analysed.

Already from what is known of the stability relations of $\gamma$-$Fe_2O_3$ it is possible to draw some definite conclusions as to the mode of origin and probable occurrence of the natural mineral. As $\gamma$-$Fe_2O_3$ is a metastable form with respect to $\alpha$-$Fe_2O_3$, it is clear that maghemite cannot be formed directly from hematite, but must be derived from other iron compounds. On the other hand, under suitable conditions of temperature and pressure maghemite readily inverts to hematite. Thus it is hardly possible for maghemite to occur as an original mineral in medium to high-temperature deposits. Maghemite appears generally to have been formed from magnetite; whether by direct oxidation or via hydrated compounds such as lepidocrocite is difficult to decide in most cases. The almost never-failing association of maghemite with limonitic material suggests that hydration and oxidation work together; however, studies on artificial $Fe_3O_4$ show that it can be easily oxidized directly to $\gamma$-$Fe_2O_3$, so that it is presumably equally possible for magnetite to oxidize directly to maghemite. In so far as maghemite is formed from lepidocrocite, its formation is controlled by the conditions determining the formation of lepidocrocite. It has been found that the formation of $\gamma$-FeOOH, the artificial substance corresponding to the mineral lepidocrocite, is largely dependent on the hydrogen-ion concentration, being formed only in weakly acid solutions (pH 2—6.5). Presumably the same limitation holds for the formation of the mineral, which may be reflected in the comparative rarity of lepidocrocite compared with goethite.

---

[1] In this connection an examination was made of the oxide formed during the disintegration of a specimen of the native iron from Ovifak preserved in the Mineralogical Institute here. However, the oxide was not maghemite, being quite non-magnetic. Powder photographs showed that it was not hematite. Presumably it was a hydrated oxide.

The natural origin of maghemite is in the zone of oxidation and weathering at the earth's surface. The only occurrence which at first sight may conflict with this is that in lavas, where it has possibly been formed by hydrothermal solutions. Ödman (72), in the description of the maghemite from the lavas of Mt. Elgon, has pointed out the practical impossibility of distinguishing between the effects of thermal waters and those of strong atmospheric weathering. A hydrothermal origin for maghemite is certainly possible, but it must have been at relatively low temperatures and pressures. All the facts indicate that maghemite could not survive metamorphic processes of any intensity, and it is therefore most unlikely that maghemite will be found as a surviving mineral from the more ancient geological periods; still, the possibility of stabilization by small quantities of foreign material must not be overlooked, even if improbable under geological conditions.

Before leaving the subject of maghemite it is perhaps desirable to take up its relationship to martite. Since martite is pseudomorphous after magnetite it might be thought that this term can be used to cover maghemite also. This, however, is not so; the original martite was a pseudomorph of hematite after magnetite, and genuine martite is thus hematite, not maghemite. The conversion of magnetite to hematite, often known as martitisation, is a distinct process from that which gives rise to maghemite. In polished sections it is generally easy to distinguish between the change from magnetite to hematite and that from magnetite to maghemite, apart altogether from the distinct optical differences between hematite and maghemite; martitisation usually follows the crystallographic directions in the magnetite, spreading along the octahedral planes from grain boundaries, cracks, and twinning lines, whereas conversion to maghemite appears to be completely independent of the crystallographic form. Perhaps this distinction reflects the difference in the nature of the two processes; the oxidation of magnetite to hematite must be discontinuous, whereas the oxidation of magnetite to maghemite can be a continuous process, oxygen atoms being continuously added to (or rather iron atoms being continuously removed from) the crystal lattice of magnetite. In this connection it may be mentioned that the change from magnetite to maghemite appears to be especially a feature of weathering under tropical conditions, but this may merely be due to the greater intensity of the weathering processes under these conditions.

To turn now to $\alpha$-$Fe_2O_3$ and hematite. Little need be said here, although $\alpha$-$Fe_2O_3$ is probably the most abundant of the iron oxides, as most of the features of this substance are thoroughly dealt with in the standard works of chemistry and mineralogy. As for $Fe_3O_4$, one is struck by the variable and even contradictory results reported by different workers for the properties of $Fe_2O_3$. This feature may be explained by experimental error, impurity or inhomogeneity of the material used, or a lack of understanding of the true nature of the substance. For example, many temperatures, ranging from 1300° to nearly 1600°, have been reported for the melting point of $Fe_2O_3$; actually $Fe_2O_3$, when heated in air, dissociates into $Fe_3O_4$ and oxygen at about 1390°, and at best the so-called melting points are simply the melting points of magnetite containing some residual $Fe_2O_3$. The melting point of hematite under sufficient pressure to prevent its dissociation has not yet been determined, but it probably lies between 1700° and 1800°.

A part of the apparent contradiction in data on $Fe_2O_3$ may be ascribed to ignorance or lack of understanding of its occurrence in two polymorphic forms. Some of the methods used for preparing $Fe_2O_3$ for investigation have undoubtedly led to the formation either of the $\gamma$-form or mixtures of this and the $\alpha$-form.

Confusion is especially marked with respect to the magnetic properties of $\alpha$-$Fe_2O_3$. It has mostly been described as paramagnetic, the ferromagnetism reported by some workers being put down to the presence of intermixed magnetite or other ferrites. However, other investigators have stated positively that $\alpha$-$Fe_2O_3$ even when quite free from $Fe_3O_4$ is ferromagnetic; thus Chaudron and Forestier (14) even determined the Curie point of $\alpha$-$Fe_2O_3$ and found that it was at 675°, considerably higher than that of magnetite (590°). This might be considered to settle to question, were it not for the recent experiments by Michel on $\gamma$-$Fe_2O_3$ stabilized by the addition of small amounts of sodium ferrite (61). He found that the (extrapolated) Curie point for $\gamma$-$Fe_2O_3$ was exactly at 675°! The supposed ferromagnetic character of $\alpha$-$Fe_2O_3$ is thus very doubtful, since a small amount of $\gamma$-$Fe_2O_3$ in the material investigated by Chaudron and Forestier would suffice to explain their results very well without the necessity of ascribing ferromagnetic properties to $\alpha$-$Fe_2O_3$.

Hematite, the mineral form of $\alpha$-$Fe_2O_3$, is extremely common and idespread. Reliable analyses on homogeneous material generally give composition close to that of pure $Fe_2O_3$. The extensive substitution of ron by other elements so characteristic of magnetite is not a feature of ematite. Ramdohr (83) showed that hematite is capable of dissolving arge amounts of $FeTiO_3$ at higher temperatures, but that this $FeTiO_3$ s generally thrown out of solution again on cooling, the solubility at rdinary temperatures being rather small. Apart from titanium, the only ther foreign element present in homogeneous hematite in any amount s magnesium, which is probably also present as dissolved $MgTiO_3$. any analyses of hematite show a minor content of FeO; however, ecent investigations have shown that solid solution of $Fe_3O_4$ in $\alpha$-$Fe_2O_3$ s very small, so that even minor amounts of FeO in an analysis are robably to be ascribed to intermixed magnetite. Magnetite accompanies ematite very frequently, and unless the analytical material has been arefully examined under the ore-microscope and shown to be free rom magnetite, a content of FeO is almost certainly due to this mineral. agnetite-hematite relations will be more thoroughly discussed in the ext section, dealing with the system FeO-$Fe_2O_3$.

## The system FeO-$Fe_2O_3$.

The system FeO-$Fe_2O_3$ is probably the most important metal oxide ystem known to man. A knowledge of the phase relations in this system s essential to the mineralogist and economic geologist who has to deal ith iron ores, and is absolutely vital to the metallurgist who has to xtract the metal from these ores in the most advantageous way. Yet t is only in the past twenty years that sufficient observations have been ade to enable the drawing-up of a phase diagram which even today s only reliable in its most essential features. This is of course largely ue to the serious practical difficulties which are inherent in a systematic nvestigation of the iron oxides; partly on account of the difficulty of ontrolling the degree of oxidation, and partly because of the lack f a suitably inert enclosing material which can withstand the attack t high temperatures of these chemically aggressive oxides. Nevertheless, ur knowledge of this system has grown so much in these twenty years hat future corrections will probably be more in the nature of changes n detail rather than in principle.

The first phase diagram for this system was published by Benedicks and Löfquist in 1927 (5, 6). They built it up by the careful selection and correlation of isolated data from many earlier investigations. The publication of this diagram apparently had a stimulating effect on

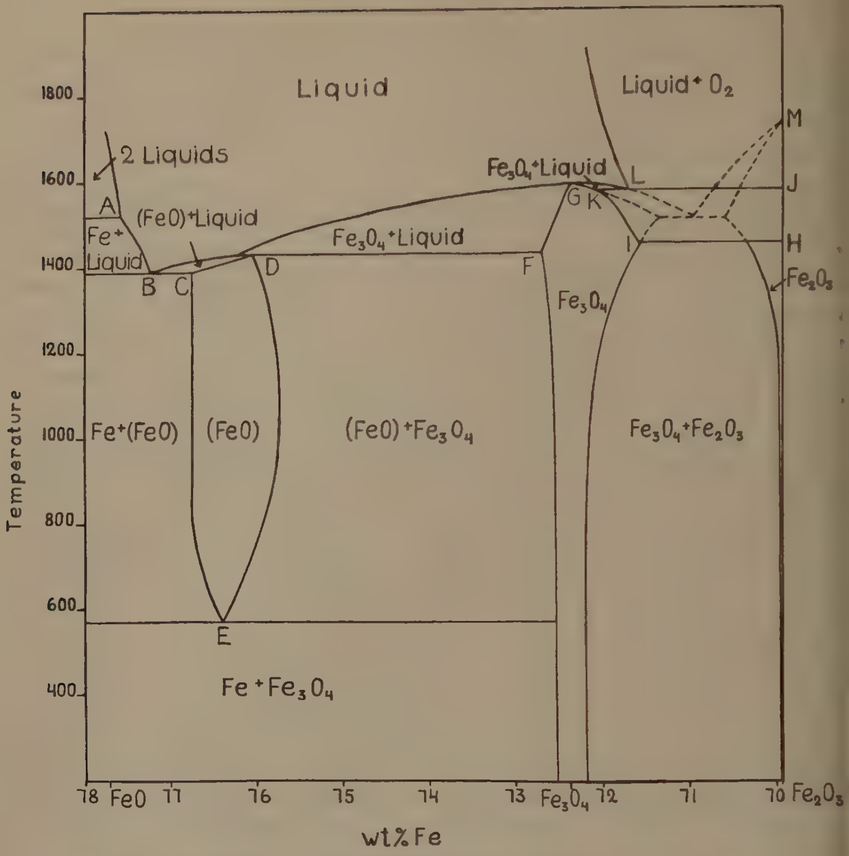


Figure 2. The system FeO-$Fe_2O_3$[1]. The symbol (FeO) represents wüstite.

researches dealing with this system, as since that time several new diagrams have been published covering the whole or part of the system — by Pfeil (81), Mathewson, Spire, and Milligan (58), H. Schenck and Hengler (90), Vogel and Martin (110), Jette and Foote (47), White, Graham, and Hay (123), Greig, Posnjak, Merwin, and Sosman (32), White (124), and Schmahl (92). Different methods have been used in the different investigations, but the agreement between the results obtained is by no means good.

This lack of agreement, however, is more in respect to subordinate features than fundamentals, and by a critical selection of data from the various investigations cited the accompanying phase rule diagram for the system FeO-$Fe_2O_3$ was constructed (Fig. 2). It does not agree entirely with any of the above mentioned investigations, but I believe that it gives at least a qualitatively correct picture of the phase relations. One of the main points of discussion in earlier works has been the liquidus-solidus relations in this system. The melting temperatures of the various phases are all so high that from the geological point of view their interest is more theoretical than real. However, for the sake of completeness they may be briefly considered here.

---

[1] Figs. 2 and 3 are more correctly described as sections of the system Fe-O.

Thus what has usually been referred to as the »melting point of FeO» is the temperature of the eutectic B between wüstite of composition C and metallic iron saturated with oxygen at that temperature. This point is usually placed at 1370°, but Jette and Foote's work suggests that it is at a somewhat higher temperature, so it is here placed at almost 1400°. Proceeding to the left from point B there is a smooth curve separating the field of iron (solid) plus liquid from that of homogeneous liquid. There is a break in this curve at 1520° (point A), at which temperature iron (saturated with oxygen) melts to a liquid which is immiscible with the liquid iron oxide with which it is in equilibrium.

The »melting point» of the wüstite phase (indicated as (FeO) in the phase diagram) varies with its composition. It rises with increasing content of oxygen, the limiting composition, D, melting incongruently at about 1430° with the liberation of solid magnetite with composition F. The liquidus curve between wüstite and magnetite is drawn in Fig. 2 as rising steadily to the melting point of pure magnetite at 1591° (G). This is the interpretation of Pfeil, and has been confirmed by Vogel and Martin, and by Jette and Foote; but other investigators claim to have observed a eutectic in this region, Mathewson and co-workers at a temperature as low as 1170°.

The determination of the melting point of $Fe_3O_4$ as 1591° is due to Greig and co-workers, and these investigators also showed that the melting point of this substance decreased with increase in oxygen content. They state that there is a eutectic between $Fe_3O_4$ and $Fe_2O_3$, but did not determine the temperature of this eutectic, the oxygen pressure at this point being too high. This is due to the thermal dissociation of $Fe_2O_3$. The diagram of this section of the system (Figs. 2 and 3) is drawn on the basis of an oxygen pressure of one atmosphere. Thus the line HI at 1452° is at the temperature of dissociation of $Fe_2O_3$ under an oxygen pressure of one atmosphere. The parallel line JK at 1573° is the melting temperature of an $Fe_3O_4$ phase saturated with oxygen at a pressure of one atmosphere. Between these two lines the stable phases are oxygen gas and an $Fe_3O_4$ phase saturated with oxygen. From the point L a curve extends in the direction of higher temperatures; it is inclined towards the left, as the dissociation tendency of the liquid increases with increased temperature.

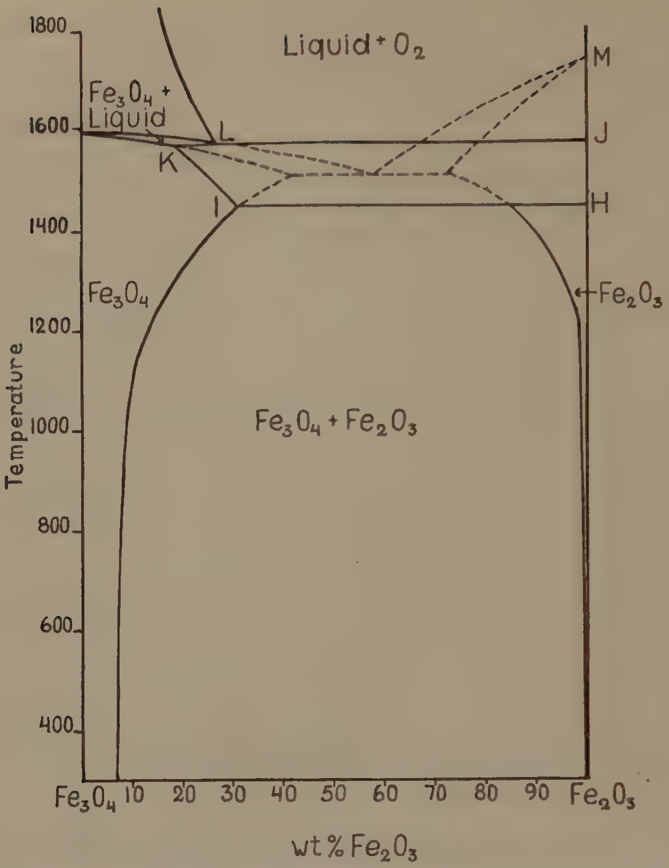


Figure 3. The system $Fe_3O_4$-$Fe_2O_3$. Solid lines indicate conditions under an oxygen pressure of one atmosphere; dotted lines conditions under a pressure sufficient to prevent the dissociation of $Fe_2O_3$.

The probable nature of the phase relationships between $Fe_3O_4$ and $Fe_2O_3$ under pressures sufficient to prevent dissociation is given by the dotted lines in Figs. 2 and 3. The melting point of pure $Fe_2O_3$ has never been accurately determined, on account of the high dissociation pressure at such a temperature; Greig and co-workers state that it appeared to be below that of platinum (1755°), which is in agreement with Pfeil, who says (81, p. 242) . . . »the melting point of the oxide approaching in composition to ferric oxide is not greatly inferior to that of platinum».

It is convenient to treat the further discussion of the phases in the system FeO-$Fe_2O_3$ in two sections, FeO-$Fe_3O_4$ and $Fe_3O_4$-$Fe_2O_3$. Of these two sections, $Fe_3O_4$-$Fe_2O_3$ is much the more important mineralogically, as it includes the vital problem of magnetite-hematite relations. The system $FeO$-$Fe_3O_4$ will therefore be dealt with rather summarily, the discussion centering around the relations between $Fe_3O_4$ and $Fe_2O_3$.

As previously pointed out, the compound FeO does not occur pure in the $FeO$-$Fe_2O_3$ system; this substance, known as ferrous oxide, or better as wüstite, always contains more oxygen than corresponds to the simple formula. The different investigators are not agreed on the precise extent of the wüstite field — the different interpretations are plotted in Fig. 1. Of all the investigations that of Jette and Foote appears to be the most exhaustive, and as the method they employed — accurate measurement of lattice dimensions by use of X-rays — is capable of great accuracy in determining homogeneity limits, their data for the wüstite field are used in Fig. 2. The triple point E, at which iron, wüstite of a fixed composition, and magnetite are in equilibrium is placed by these authors at 76.4 % Fe. The temperature of this point has been placed by different workers between 560° and 575°. Below this point wüstite is no longer a stable phase, but tends to break up into metallic iron and magnetite, according to the equation

$$4FeO = Fe + Fe_3O_4$$

This reaction takes place with evolution of heat, the heat of the reaction, according to the newest data of Roth and Wienert (86), being 8200 ± 700 calories at 20.7°. The disintegration of wüstite below 575° is, however, rather sluggish, and by rapid cooling this phase can be preserved at ordinary temperatures. According to Chaudron and Forestier (13), the disintegration is most rapid at 480°, at which temperature 80 % of the wüstite decomposes into metallic iron and magnetite in 24 hours.

Turning now to the $Fe_3O_4$ side of the $FeO$-$Fe_3O_4$ system, we have the interesting mineralogical problem of possible solid solution of FeO in magnetite. Here there is practically no conflict between the various investigations on artificial preparations; all concur in giving a very low figure — no more than 3 wt.% FeO — for the limiting solid solution, at least below about 1200°. Thus it would appear that in magnetites whose analyses show a considerable excess of FeO, the excess is either accounted for by the presence of foreign elements, such as titanium, in solid solution, or the analysed material was inhomogeneous. Many published analyses of magnetite show considerable excesses of FeO, but an attempt to interpret these analyses offers few prospects, as the uncontrolled sources of error in the most cases invalidates any conclusions that might be drawn. The few more or less convincing descriptions of magnetites with excess FeO, such as that of Palmunen (76), all appear to be of magnetites from titanium-rich basic igneous rocks, and it is perhaps not unlikely that this excess FeO was present in a titanium spinel in solid solution with the magnetite molecule.

Turning now to the system $Fe_3O_4$-$Fe_2O_3$, the first systematic investigation was that of Sosman and Hostetter in 1916 (98). They studied the dissociation pressures of these oxides at 1200°, and came to the conclusion that at this temperature there was continuous or practically continuous solid solution between $Fe_2O_3$ and $Fe_3O_4$. Since then several researches on this system have been published, and all subsequent investigators have concluded that continuous solid solution does not exist, although disagreeing among themselves as to the extent of the hiatus. The interpretation expressed in Figs. 2 and 3 is largely built up on the basis of the painstaking and thorough investigation of Greig and his co-workers (32). The results of Greig and co-workers indicate that the solubility of $Fe_3O_4$ in $Fe_2O_3$ is very small at all temperatures up to 1450°, whereas the solubility of $Fe_2O_3$ in $Fe_3O_4$ is small but noticeable at low temperatures and rapidly increases at high temperatures, reaching 30 wt.% at about 1450°. Compared with previous workers, they found generally a much smaller solubility of $Fe_3O_4$ in $Fe_2O_3$, and a greater solubility of $Fe_2O_3$ in $Fe_3O_4$. These results have since been largely confirmed by the investigations of White (124), and of Schmahl (92). The agreement for the course of the solubility curve of $Fe_2O_3$ in $Fe_3O_4$ is practically complete. White, however, found a somewhat greater solubility of $Fe_3O_4$ in $Fe_2O_3$ than did Greig and his co-workers, but Schmahl has pointed out certain methodical defects in White's work sufficient to account for the too high solubility that he found. The best of the available data indicates that the solubility of $Fe_3O_4$ in $Fe_2O_3$, at least below 1300°, is very small indeed, 1 wt.% or less.

The systematic investigations of the $Fe_3O_4$-$Fe_2O_3$ system have all been carried out at high temperatures, 1100° and above, so the course of the phase boundary curves at lower temperatures represents a considerable extrapolation. Since the amount of solid solution of $Fe_3O_4$ in $Fe_2O_3$ is very small even at high temperatures, the extrapolation in this case cannot lead to any great error. The solubility of $Fe_2O_3$ in $Fe_3O_4$, however, is sufficiently great to render an extrapolation from 1100° down to ordinary temperatures somewhat venturesome. Indirectly, however, confirmation of the course of the curve bounding the magnetite field at lower temperatures is given by the work of Hägg (35) on $\gamma$-$Fe_2O_3$. By heating samples of products intermediate between $Fe_3O_4$ and $\gamma$-$Fe_2O_3$ in sealed tubes for a sufficient time at 675° and 490° he decomposed them into $\alpha$-$Fe_2O_3$ and the magnetite solid solution in equilibrium with excess $Fe_2O_3$ at these temperatures. By careful measurement of the lattice dimensions of the magnetite phase thus formed he could show that it contained more oxygen than corresponded to the formula $Fe_3O_4$. The composition corresponded to a formula $FeO_{1.344}$, viz., an $Fe_3O_4$ with 7 wt. % $Fe_2O_3$ in solid solution. On the basis of this data the bounding curve for the magnetite phase has been extrapolated to low temperatures.

From the above results on artificial preparations it is evident that under ordinary conditions pure magnetite can contain up to about 7 wt. % $Fe_2O_3$ in solid solution, whereas hematite must correspond almost exactly to the formula $Fe_2O_3$, the presence of only a small amount of FeO leading to the formation of a magnetite phase. The numerous investigations on the natural minerals confirm this reasoning and the general correctness of the phase diagram (Fig. 3) on which it is based. Certainly the paper of Sosman and Hostetter (98) postulating complete mutual solubility of $Fe_3O_4$ and $Fe_2O_3$ was followed by another by the same investigators on natural occurrences of $Fe_3O_4$ and $Fe_2O_3$ which they claimed supported their laboratory results (99). However, subsequent workers on magnetite and hematite have contested these results, and investigations of polished sections have shown that the material considered by Sosman and Hostetter to be solid solutions of the two minerals was undoubtedly heterogeneous. Most interesting in this connection is Fig. 228 in Schneiderhöhn and Ramdohr's book (93); this shows an inclusion from a basalt in which well-defined hematite and magnetite occur in a typically recrystallized state, but without any sign of solid solution in each other, as should be expected if the results of Sosman and Hostetter were correct.

Since the solubility of $Fe_2O_3$ in $Fe_3O_4$ does not begin to increase rapidly until over 1100°, the possibility of finding natural magnetites with 10 wt. % or more $Fe_2O_3$ in solid solution must be very small. If such magnetites are ever formed, then from the phase diagram it is evident that on cooling the excess $Fe_2O_3$ should be liberated from the now oversaturated solid solution as oriented inclusions of hematite. Such substances were prepared artificially by Greig and his co-workers, and illustrations in their paper show unmixed hematite in a groundmass of magnetite. These artificial preparations had a structure typical of unmixing in magnetite, regular lamellae of hematite having separated out along the octahedral planes in the magnetite. The structure was identical with that shown by the many unmixed titanomagnetites described from natural occurrences.

Since temperatures of 1100°—1200° and higher are necessary to increase the solubility of $Fe_2O_3$ in $Fe_3O_4$ so much that on cooling unmixing will tend to take place, it is doubtful whether oriented intergrowths of hematite in magnetite formed in this way will be found in nature. The only mention of such an occurrence known to me is in a paper by Newhouse (69) describing the opaque minerals observed in 265 different igneous rocks. In one specimen, a basalt from the 1886 eruption of Mt. Etna, he records what he considers to be exsolved hematite in magnetite. His drawing shows regular lamellae of hematite along the octahedral planes of the magnetite, and resembles closely the artificial preparations of Greig and co-workers. In this connection I was able to examine a rather comprehensive collection of polished sections of lavas belonging to Dr. Ödman of the Swedish Geological Survey. Magnetite was present in practically all these sections, often together with hematite, but in none of them did the hematite appear to be due to the unmixing of a once-homogeneous solid solution. When hematite was present, it always appeared to be secondary after magnetite. Here it should be pointed out that at first glance the replacement structures of hematite in magnetite often resemble the regular intergrowths formed by unmixing of a solid solution. On closer scrutiny, however, the distinctions are easily seen. Replacement of magnetite by hematite often follows the octahedral planes, giving rise to a network of hematite lamellae, but this replacement proceeds from grain boundaries and cracks, so that the structure is clearly governed by these features, and is not as regular and continuous as the structure produced by unmixing. The hematite lamellae produced by replacement also vary considerably in width in different parts, whereas lamellae produced by exsolution are typically of very uniform width.

The important feature of magnetite-hematite relations is the problem of the conversion of the one mineral into the other in natural occurrences. There is a considerable literature on this subject, as such conversion, or replacement of the one mineral by the other, is extremely common. Most descriptions have dealt with the replacement of magnetite by hematite, often known as martitisation, but the reverse process is by no means rare. In fact, in Sweden at least it is often a typical feature of the iron ores.

In general the conversion of hematite to magnetite appears to be characteristic of medium to high grade metamorphism. There has been a tendency to ascribe this conversion of hematite to magnetite to thermal metamorphism, the raising of the temperature under metamorphism being evidently considered as causing a dissociation of the hematite. Such a hypothesis is, however, scarcely tenable in view of the stability relations of $Fe_2O_3$. $Fe_2O_3$ is stable when heated in air up to a temperature of 1388°, at which point its dissociation pressure reaches 159 mm., the partial pressure of oxygen in the atmosphere. Even when heated in a stream of neutral gas, such as nitrogen, the dissociation of $Fe_2O_3$

is practically zero at temperatures up to 1200°. Therefore under the conditions we are accustomed to reckon with during metamorphism hematite will show no tendency to dissociate, especially as the pressure ruling will increase the stability of the hematite still further.

Since thermal metamorphism alone cannot convert hematite to magnetite, the process must involve metasomatic reactions, clearly of a reducing nature. The question is therefore to discover the reducing agents which have been active, and their source. Many substances may act as reducing agents, the most common naturally occurring being probably compounds of carbon, hydrogen, and sulphur. Often the source of such reducing agents can be shown to have been magmatic, as when the change from hematite to magnetite is clearly the result of contact action. This is well seen in many mines of central Sweden, where pegmatite dikes cut hematite ores; these dikes are bounded by a zone of magnetite, evidently due to the reducing effect of the pegmatite fluids on the hematite. Shepherd's study of the gases in lavas and igneous rocks (96) has shown that these always contain reducing agents such as $H_2$, $CO$, $SO_2$, and $S_2$. Thus the effect of magmatic fluids on $Fe_2O_3$ may be represented by the following equations:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$$
$$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$$

Experimental studies have shown that equilibrium in these reactions lies so far towards the right that they can be considered as practically irreversible.[1] That is to say, even in the presence of an extremely small concentration of $CO$ or $H_2$, $Fe_2O_3$ is no longer stable and is reduced to $Fe_3O_4$. Increasing temperature has little effect on the reduction other than to increase the rate of the reaction. Pressure is without influence, as there are equal amounts of gas on both sides of the above equations.

Carbon monoxide and hydrogen are extremely potent reducing agents for $Fe_2O_3$. As can be seen from the equations, one part of $CO$ will completely convert about 17 times its own weight of hematite to magnetite, and one part of hydrogen almost 240 times its own weight of hematite to magnetite. Other reducing agents are also very effective in the alteration of hematite to magnetite. Sulphur dioxide, and less oxidized sulphur compounds reduce trivalent iron at moderate temperatures. This effect is probably reflected in the presence of magnetite in many sulphide deposits.

Summing up, it may be said that the conversion of hematite to magnetite requires the action of reducing agents. The geological conditions of the alteration of hematite to magnetite are those of medium to high grade metamorphism, and of the contact action of igneous intrusions. It is reasonable to ascribe at least a considerable part of the alteration of hematite to magnetite to the reducing action of compounds of carbon, hydrogen, and sulphur, the source of which may be magmatic.

---

[1] In this connection, the practical absence of primary hematite from igneous rocks, except perhaps in the more acid granites, is significant.

The reverse process, the change from magnetite to hematite, is common and widespread. From the previous discussion, it is clear that magnetite can only be directly changed to hematite in the total absence of reducing agents. On the other hand, however, under favourable conditions this change takes place readily enough in a weakly oxidizing milieu. Gruner (34) showed that magnetite heated in air at 150°—200° is slowly oxidized to hematite, the oxidation beginning along the octahedral planes in the magnetite, just as observed in natural occurrences. Magnetite will evidently readily change to hematite under conditions of moderate temperature and sufficient supply of oxygen. In conformity with the above facts, the change from magnetite to hematite in nature appears on the whole to be confined to the zone of oxidation close to the earth's surface. The process is one of weathering or of only a low grade of metamorphism. In ore bodies it can often be established that the alteration of magnetite to hematite is the work of descending solutions.

An important influence in the oxidation of divalent to trivalent iron, and one which has apparently been overlooked by mineralogists, is the pH of the medium in which the reaction takes place. The oxidation of ferrous to ferric iron takes place much more readily in alkaline than in neutral or acid solutions. The oxidation-reduction potential of the reaction $Fe(OH)_2 \rightarrow Fe(OH)_3$ is $-0.65$ volt, that of the reaction $Fe^{\cdot\cdot} \rightarrow Fe^{\cdot\cdot\cdot}$ is $+0.75$ volt. Thus $Fe(OH)_2$ liberates hydrogen from water with the formation of $Fe(OH)_3$, whereas in acid solution hydrogen will reduce ferric iron to ferrous iron. Alkaline solutions therefore, even without the presence of atmospheric oxygen, probably have an oxidizing effect on magnetite, whereas acid or neutral solutions do not have this effect. It is tempting to suggest that some of the examples that have been described as the direct oxidation of magnetite to hematite may have been actually indirect, over the hydrated oxides, these having later been dehydrated to give hematite. It is not always easy to distinguish between the ferric oxide hydrates and hematite in polished sections where they replace magnetite, especially when they are present as fine lamellae.

It must be emphasised that chemical factors alone do not fully determine the degree or extent of the replacement of hematite by magnetite or vice versa. The physical features of the rock of which the minerals form a part — the porosity, the grain size, the presence or absence of fissures, tectonic strains, etc. — all play a part in promoting or retarding the change, and must be taken into account when evaluating the conditions of replacement.

In conclusion, it is worth pointing out that the change from hematite to magnetite is accompanied by a slight but measurable decrease in volume, the reverse change with an equivalent increase in volume. The amount of change amounts to about 2.5 %. This figure is derived from the specific gravities calculated from the accepted figures for the unit cell dimensions of magnetite and hematite. Three molecules of $Fe_2O_3$ give two molecules of $Fe_3O_4$. Thus 479 grams $Fe_2O_3$ (S. G. 5.25) give 463 grams $Fe_3O_4$ (S. G. 5.20), the corresponding volumes being 91.25 cc. and 89.04 cc. respectively, a percentage decrease of 2.5. Gruner (34) made a similar calculation in 1926, but on account of lack of accurate measurements of the unit cell dimensions of magnetite and hematite in those days, he came to a result, 5.2 %, which is considerably too high.

## The manganese oxides.

### MnO — Manganosite.

Unlike ferrous oxide, manganous oxide with a composition corresponding to the formula MnO occurs both as a laboratory product and as the mineral manganosite. When pure it is a green solid, but it is unstable under atmospheric conditions, readily oxidizing and becoming brown to black through transformation to higher oxides. It may be prepared by heating manganous carbonate, oxalate, or hydroxide out of contact with air, or by reducing higher oxides in a stream of hydrogen.

MnO is cubic, with a structure of the NaCl type, the unit cell containing four MnO. Several investigators have determined the edge of the unit cube; the most reliable figure is apparently that of Broch (9), and Ruhemann (87), who both obtained $a = 4.435$ A at room temperature. The calculated density is thus 5.36; the measured density is 5.18 (Blomstrand, 8) and 5.346 (Palache, 75) on the mineral, and 5.432 (Levi, 53) on the fused laboratory product. Blomstrand's value is evidently somewhat low. Several temperatures have been given for the melting point of MnO, ranging from 1585° upwards; the latest, and also the highest figure is 1785° (Hay, Howat, and White, 37), and is probably the most accurate.

MnO as a mineral was first described from Långban in 1874 by Blomstrand (8), who named it manganosite. Since then it has been found at three other localities, Nordmarken in Sweden, Franklin in the U. S. A., and the Kaso mine in Japan. At the last two localities it is apparently rare, and it is not common at the Swedish localities, although it has occasionally been found in rather large quantities. No specimens have been found at Långban in recent years, but when I was in Nordmarken in the summer of 1942 I was able to collect specimens of a dolomite with plentiful grains of manganosite from a restricted occurrence on the 143-metre level in the mine. At Långban and Nordmarken manganosite occurs as small grains in a manganiferous dolomite, and has evidently been formed by the metamorphism of a mixture of calcium, magnesium, and manganese carbonates. On heating, manganese carbonate decomposes into MnO and $CO_2$ at a relatively low temperature, lower than either $CaCO_3$ or $MgCO_3$, and this reaction is responsible for the formation of manganosite. Manganosite alters readily under conditions of oxidation or hydration, the alteration being promoted by an alkaline medium; most specimens of manganosite rapidly become covered by a brownish-black coating when exposed to the atmosphere, and thin sections of specimens from Långban and Nordmarken generally show a core of fresh manganosite with a coating of pyrochroite, which in turn is partly changed to manganite.

At high temperatures MnO forms solid solutions with other oxides of the RO type, and such solid solutions of MnO with FeO and MgO are often found as phases present in basic slags. Analyses of manganosite show that it is practically pure MnO. The solubility of other oxides in MnO evidently decreases greatly at lower temperatures. Frondel (28) recently described exsolution intergrowths of zincite in manganosite from Franklin, and of manganosite in periclase from Långban and Nordmarken, indicating that the mutual solubility of MnO and ZnO and of MnO and MgO must be quite small at ordinary temperatures.

### $Mn_3O_4$ — Hausmannite.

The most stable oxide of manganese at high temperatures is $Mn_3O_4$, and it is easily prepared in the laboratory by heating any of the other oxides at about 1000° in air. When obtained in this way it is a red-brown powder, but several methods have been described for obtaining it as crystals. The symmetry of $Mn_3O_4$ is lower than that of $Fe_3O_4$, being tetragonal instead of cubic. The structure of $Mn_3O_4$ was determined by Aminoff (1), who showed that, although tetragonal, it was similar to that of $Fe_3O_4$, being a deformed spinel type. The lattice dimensions are $a = 8.14$ A, $c = 9.42$ A (compare $Fe_3O_4$ $a = 8.38$ A). The volume of the unit cell of $Mn_3O_4$ is somewhat greater than that of $Fe_3O_4$, as the atoms of manganese are rather larger than those of iron.

The only determination of the melting point of $Mn_3O_4$ is that of von Wartenberg and his co-workers (118), who give it as 1560°. An earlier determination, 1705°, by von Wartenburg and Gurr (117), which is sometimes cited, was erroneous, due to the use of a faulty pyrometer.

The mineral form of $Mn_3O_4$, hausmannite, was first recognised by Werner. It is not common, but is widespread, sometimes occurring in considerable masses, as at Långban, where it is an important manganese ore. It is often found as black lustrous pyramidal crystals. The most characteristic feature of hausmannite is the reddish-brown streak, which serves to distinguish it from many other black ore minerals. In very thin fragments it is not fully opaque, having a dark red-brown colour. It is easy to recognize in polished sections of manganese ores by the beautiful red internal reflections, and a typical lamellar twinning, but the latter feature is not fully reliable, as on rare occasions hausmannite may be quite untwinned.

Analyses show that hausmannite is generally practically pure $Mn_3O_4$, there being little replacement of manganese by other elements. Iron is often present in small amounts, but the greatest amount previously recorded is 5.75 % $Fe_2O_3$ in a specimen from Jakobsberg (Gorgeu, 30). During this investigation some iron-rich homogeneous crystals of hausmannite from Långban were found and analysed (microchemically by Miss Anna-Greta Hybbinette, to whom I would express my grateful thanks). They contained 6.91 % $Fe_3O_4$, and this appears to be close to the limiting replacement at ordinary temperatures. A little magnesium is sometimes present, and in specimens from Ilmenau up to 8.6 % ZnO (29). These zinc-bearing hausmannites are evidently connecting links between $Mn_3O_4$ and hetaerolite, the naturally occuring $ZnMn_2O_4$. The divalent manganese in $Mn_3O_4$ can probably be completely replaced by other metals without change of structure; Gorgeu (31) made pyramidal crystals like those of hausmannite in which part of the manganese was replaced by cadmium, zinc, and magnesium, by fusing together the respective sulphates in the desired proportions.

The recorded specific gravity of hausmannite varies from 4.72 to 4.91, the latter figure being for a specimen with 7.2 % ZnO. The specific gravity calculated from X-ray data is 4.84. Hausmannite is paramagnetic, and the magnetic properties vary only slightly with the small amount of iron sometimes present in solid solution.

## $Mn_2O_3$ — Bixbyite.

Unlike the lower oxides of manganese, $Mn_2O_3$ is polymorphic. No less than three different forms have been described: the common form, and the only stable one, here referred to as $\alpha$-$Mn_2O_3$; $\gamma$-$Mn_2O_3$, corresponding to $\gamma$-$Fe_2O_3$, being a metastable form with the same tetragonal structure as $Mn_3O_4$ but with empty metal positions; and a third form, also tetragonal, but perhaps distinct from $\gamma$-$Mn_2O_3$. Only $\alpha$-$Mn_2O_3$ is known as a mineral, so the other forms will only be dealt with summarily.

The history of $\gamma$-$Mn_2O_3$ is short and the literature on it small. It was first described by Dubois in 1934 (18, 19).[1] He precipitated a manganic oxide hydrate by adding alkali to a boiling solution of manganous sulphate in the presence of hydrogen peroxide. By drying this precipitate at room temperature and carefully dehydrating at 250° in a vacuum he obtained an easily oxidizable oxide with composition $Mn_2O_3$, which gave a powder photograph different from the known modification of $Mn_2O_3$ ($\alpha$-$Mn_2O_3$) but closely resembling that of $Mn_3O_4$. He obtained the same substance by the thermal decomposition of manganous oxalate in a stream of air. His experiments were repeated by Verwey and de Boer (109), who succeeded in preparing a very hygroscopic oxide containing 9.94 wt. % active oxygen (calculated for $Mn_2O_3$ 10.14 %), and losing 4.0 % in weight on ignition in air (calculated 3.38 %). They showed that it was analogous to the $\gamma$-form of $Fe_2O_3$ and therefore proposed the indication $\gamma$-$Mn_2O_3$. On the basis of the same arguments as used in the discussion on the structure of $\gamma$-$Fe_2O_3$ the crystal structure of $\gamma$-$Mn_2O_3$ can be described as an $Mn_3O_4$ lattice with $2^2/_3$ vacant cation positions per unit cell. Verwey and de Boer found the lattice dimensions of $\gamma$-$Mn_2O_3$ to be $a = 8.1$ A, $c = 9.4$ A, $c/a = 1.16$. The specific gravity was approximately 4.6, much lower than that of the stable $\alpha$-$Mn_2O_3$.

In this connection it is interesting to note that Pavlovitch (78) states that he has obtained this $\gamma$-$Mn_2O_3$ by heating polianite in air for twelve hours at 550—600°. The polianite lost 9.80 % of its weight and the black powder thus obtained, although $Mn_2O_3$, gave a powder photograph similar to that of hausmannite. I repeated Pavlovitch's experiment by heating a specimen of polianite from Platten in Bohemia in an electric furnace for twelve hours at 570°, but failed to reproduce his result, the product being the common or $\alpha$-form of $Mn_2O_3$.

---

[1] Dubois called this oxide $\alpha$-$Mn_2O_3$ and the common form $\beta$-$Mn_2O_3$. However, in view of the analogies with the forms of $Fe_2O_3$ the nomenclature used in this paper is more logical.

The other metastable form of $Mn_2O_3$ was described by Le Blanc and Wehner in 1933 (52). They obtained it by the addition of oxygen at temperatures of 350° and 400° to an active MnO prepared by the decomposition of $MnCO_3$ in vacuum. It was a black powder, so fine-grained that it was difficult to get satisfactory powder photographs. However, with the aid of the graphical tables they succeeded in interpreting the powder photographs, and state that the substance is probably tetragonal, with lattice dimensions $a = 8.85$ A, $c = 9.95$ A. On heating in a closed tube for four weeks at 420° it completely inverted to $\alpha$-$Mn_2O_3$. The properties of this form are very similar to those of $\gamma$-$Mn_2O_3$ and Dubois (18, p. 1418) suggests that they may be identical. However, according to the description of Le Blanc and Wehner the powder photograph of their oxide is different from that of $Mn_3O_4$.

The stable form, $\alpha$-$Mn_2O_3$, hereafter referred to simply as $Mn_2O_3$, has long been known. Many methods have been described for preparing it; a simple and satisfactory method, which was used in this investigation, is to precipitate a solution of manganous sulphate with sodium hydroxide, wash the precipitate until free from sulphate, dry in an oven somewhat above 100°, and heat the product at 700° for some hours with free access of air. $Mn_2O_3$ is the stable oxide of manganese in air between about 530° and 940°. $MnO_2$ loses oxygen and is converted into $Mn_2O_3$ at about 530°, and $Mn_2O_3$ itself loses oxygen at 940° and is converted into $Mn_3O_4$. On account of this dissociation the melting-point of $Mn_2O_3$ is unknown.

The symmetry and crystal structure of $Mn_2O_3$ were first investigated by Zachariasen (128, 129). He found that it had a body-centred cubic lattice with $a = 9.40$ A, and belonged to the so-called C-type of the sesquioxides, being isomorphous with many of the oxides of the rare earth metals — $Sc_2O_3$, $Y_2O_3$, $Sm_2O_3$, $Eu_2O_3$, $Gd_2O_3$, $Tb_2O_3$, $Dy_2O_3$, $Ho_2O_3$, $Er_2O_3$, $Tm_2O_3$, $Yb_2O_3$, $Lu_2O_3$ — and also with $In_2O_3$ and $Tl_2O_3$. Zachariasen deduced that the space group of the C-type of the sesquioxides was $T_5$ and proposed a structure to conform with this, but Pauling and Shappell (77) have shown that his conclusions were erroneous, the space group being not $T_5$ but the more symmetrical $T_h^7$. On this basis they were able to derive a satisfactory structure for $Mn_2O_3$ and the other sesquioxides of the C-type.

The most noteworthy feature is that $Mn_2O_3$ is not isomorphous with $Fe_2O_3$, $Fe_2O_3$ being rhombohedral and having the corundum structure. Zachariasen discussed this feature and showed that it depended on the radius of the metal ion. Trivalent metals having an ionic radius of 0.60—0.72 A had oxides of the corundum type, and trivalent metals with ionic radius 0.73 A—1.05 A had oxides of the C-type. $Mn^{\cdot\cdot\cdot}$, with an ionic radius of 0.73 A, was the smallest ion to give rise to an oxide of the C-type; $Fe^{\cdot\cdot\cdot}$, radius 0.70 A. formed an oxide with the corundum structure. The ionic radii of trivalent manganese and trivalent iron being so close, it is tempting to speculate on the possibility of an unstable form of $Mn_2O_3$ with the same structure as hematite. So far, however, such a substance has not been recognized; it would conceivably be stable under extremely high pressure, as the corundum structure is more close-packed than the C-type structure.

The occurrences of $Mn_2O_3$ as a mineral always contain iron in solid solution, replacing manganese up to about 50 % or a little more. The original discovery was by Penfield and Foote (79), who named the mineral bixbyite; in their material the proportion Mn : Fe was almost exactly 1 : 1, and they formulated it as a ferrous manganite of fixed composition, $FeO \cdot MnO_2$, rather than as a solid solution of $Fe_2O_3$ in $Mn_2O_3$, $(Mn, Fe)_2O_3$, in which the amount of $Fe_2O_3$ can vary from nil up to 50 % or even more. Zachariasen, who also investigated bixbyite röntgenographically, showed however that bixbyite had the same structure as $Mn_2O_3$ and was therefore to be considered as $(Fe, Mn)_2O_3$. not as a definite compound of FeO and $MnO_2$.

The occurrences of bixbyite were discussed in an earlier paper (Mason, 57), describing a find of bixbyite at Långban. In that paper it was shown that the mineral sitaparite, first described by Fermor in 1908 (21) from the manganese ores of Sitapar in India, was structurally identical with bixbyite. The name sitaparite was discarded, bixbyite having priority. The analysis of sitaparite published by Fermor agrees with the formula $(Mn, Fe)_2O_3$, save for the presence of about 6 % CaO. From Fermor's description the material for analysis was homogeneous, so the presence of the calcium can hardly be ascribed to mechanical impurities. It is conceivable that it is present in solid solution in such a grouping as $CaMnO_3$.

Bixbyite occurs in two quite distinct parageneses. Penfield and Foote's bixbyite from Utah, and the bixbyite from Patagonia are of pneumatolytic origin, occurring in close connection with acid extrusives; bixbyite from Sitapar, from Postmasburg, and from Långban occur in metamorphosed manganese ores. In a recent discovery of ore boulders near Murjek in Northern Sweden (as yet undescribed) bixbyite also occurs as a phase in a metamorphosed manganese ore. The different parageneses are reflected in the composition of the bixbyite, and will be discussed in connection with the system $Fe_2O_3$—$Mn_2O_3$.

The recorded specific gravity of bixbyite varies from 4.74 to 5.09. The specific gravity of $Mn_2O_3$ calculated from the X-ray data ($a$ = 9.40 A) is 5.01. Bixbyite shows great power of crystallization, often occurring as well-formed cubic crystals, and in the metamorphosed manganese ores it is generally present as idioblasts in a groundmass of other minerals.

## $3\,Mn_2O_3 \cdot MnSiO_3$ — Braunite.

Strictly speaking, braunite does not belong to the group of oxides discussed in this paper, as it contains not only manganese but also silicon as an essential element in its structure. For many years, however, braunite was looked upon merely as a variety of $Mn_2O_3$, and as it is closely related to this substance and not to the manganese silicates, no apology is needed for devoting some space to the consideration of this interesting compound.

Braunite was named after Kammerrat Braun of Gotha, who sent the original material of this species (from Elgersburg in Thuringia) to Haidinger and Turner. Haidinger, who proposed the name braunite, decided that this mineral was naturally occurring $Mn_2O_3$, on the basis of Turner's analysis, according to which it was practically pure $Mn_2O_3$ with only a trace of silica. Later analyses of braunite from Thuringia, as from other localities, showed 8 % and more $SiO_2$, and for many years the question as to whether or not this silica was an essential constituent of braunite was hotly argued. Some held that the silica arose from mechanically admixed silicate in the analysed material, others that it was constitutional; those holding the latter viewpoint were further divided, some saying that the amount of silica present was variable, replacing tetravalent manganese in the formula $MnO \cdot (Mn, Si)O_2$, others that it was fixed, being present in the proportion of one $MnSiO_3$ group to three $Mn_2O_3$. The question was not finally answered until 1931, when Aminoff published the results of an X-ray study on braunite (2). He showed that braunite had a structure related to, but distinct from that of $Mn_2O_3$, and that its formula was $3\,Mn_2O_3 \cdot MnSiO_3$. Even today, however, the distinction is not always appreciated; for example, in a recent book on manganese ores braunite is described as $Mn_2O_3$, containing 69.6 % Mn. This failure to perceive the difference between braunite and $Mn_2O_3$ may be due to erroneous statements such as that of Le Blanc and Wehner (52, p. 67), who state that braunite and bixbyite give identical powder photographs. Although some of the strong lines in powder photographs of these two substances coincide, the general pattern is quite distinct.

The crystal structure of braunite was recently determined by Byström and the writer (11). As Aminoff suggested, the structure is related to that of bixbyite, the unit cell of braunite being just twice as large as that of bixbyite, consisting geometrically of two unit cubes of bixbyite joined together. The lattice dimensions of braunite from different localities show little variation, *a* being 9.40—9.42 A, *c* 18.59—18.72 A. With the lattice dimensions $a = 9.41$ A, $c = 18.64$ A (those of a synthetically prepared braunite) the calculated specific gravity is 4.83. The recorded specific gravity of the natural mineral varies from 4.72—4.82.

The amount of $SiO_2$ required by the formula $3\,Mn_2O_3 \cdot MnSiO_3$ is 10.0 wt.% and most analyses of braunite show silica percentages close to this figure. Two analyses, however, appear in mineralogical handbooks which show practically no silica, one of a specimen from Arkansas with 0.18 % $SiO_2$ and one of a specimen from Elba with 0.75 % $SiO_2$. Miser and Fairchild (63) have shown that the supposed silica-free braunite from Arkansas was inhomogeneous, being a mixture of psilomelane and hausmannite. As far as I know, nothing has been published on the occurrence of braunite on Elba since the paper in which the analysis was given (59), and that gives no information save that the material was »compact braunite». Either the analysis is faulty, the material inhomogeneous, or the mineral was not braunite at all, but bixbyite.

The amount of foreign elements replacing manganese in braunite is generally rather small. The most common replacing element is iron, but the amount present seldom exceeds 5 % $Fe_2O_3$. The greatest amount of $Fe_2O_3$ recorded in any analysis of braunite is 15.39 % in a specimen from Mason County, Texas (40); this specimen had been polished and examined under the ore-microscope before analysis and found to be homogeneous, so that the $Fe_2O_3$ was certainly present in solid solution, not as intermixed hematite. It is probable that the amount of replacement of manganese by iron in braunite is rather limited, as all attempts to make iron-rich braunites synthetically during the course of this investigation were unsuccessful, although the synthesis of ordinary braunite, as described below, is by no means difficult. Only small amounts of elements other than iron have been recorded in analyses of braunite, the maxima being 4.36 % MgO, 4.28 % CaO, and 1 % or a little more BaO. The greatest amount of replacement by these elements in any braunite is in the braunite from Kajlidongri, India, described by Fermor (22), which contained 4.36 % MgO and 3.85 % CaO; as Fermor pointed out, this corresponds almost exactly to the formula $3\,Mn_2O_3 \cdot (Mg, Ca)SiO_3$, suggesting that magnesium and calcium replace the manganese atoms grouped with silica. In the synthetic experiments in connection with this paper it was possible to confirm this in the following way. An intimate mixture of $Mn_2O_3$ with the precipitate obtained by adding $Na_2SiO_3$ to a mixed solution of magnesium and calcium salts in the correct proportions to give $(MgCa)SiO_3$ was heated for three days at 930°. The powder photograph of the product was identical in every respect with that of natural braunite. A similar mixture of $Mn_2O_3$ and precipitated $MgSiO_3$ heated in the same way also gave a product corresponding to braunite. On the other hand, no reaction was obtained when $Mn_2O_3$ was heated in this way with finely powdered diopside or enstatite; this is evidently due to the unreactive nature of the crystallized minerals as compared with the semi-amorphous products obtained by precipitation from solutions at ordinary temperatures.

Several methods are described in different handbooks of mineralogy for preparing braunite synthetically, but owing to the lack of understanding of the essential nature of the silica, these methods give only artificial bixbyite, $Mn_2O_3$. Braunite is easily synthesised, however, by precipitating a manganous salt solution with a mixed solution of sodium hydroxide and sodium silicate and heating the precipitate in air for some hours at about 900°. The reaction probably takes place quite readily at lower temperatures also, but I have not investigated this. During this investigation braunite was also synthesised by heating a finely-powdered mixture of $Mn_2O_3$ and rhodonite in the proportions corresponding to $3\,Mn_2O_3 \cdot MnSiO_3$ for several days at 900°.

It has previously been a matter of some surprise that braunite is such an individual substance, not being isomorphous with any other mineral. The reason is not far to seek. From structural considerations it is apparent that the only elements likely to form compounds isomorphous with braunite are those with sesquioxides of the C-type, viz. the rare earths and indium and thallium. Oxide minerals of these elements are unknown, so that it is extremely unlikely that any compound of these elements related to braunite will be found in nature. Scandium being the trivalent element with ionic radius nearest that of manganese, it would be interesting to try to synthesise a compound $3Sc_2O_3 \cdot ScSiO_3$, which should be isomorphous with braunite; unfortunately I have not had the necessary material to attempt such a synthesis.

Braunite is not a rare mineral, and in some places it occurs in sufficient quantities to be an important ore of manganese. It is common in metamorphosed manganese deposits. From the number of localities recorded for braunite it appears to be much more common than bixbyite, but I am not convinced that bixbyite is as rare as it seems. When massive, bixbyite and braunite cannot be distinguished save by chemical tests for the presence or absence of silica, or by powder photographs. Even in polished sections I have often found it impossible to certainly distinguish bixbyite and braunite by their optical properties alone. Braunite is tetragonal, and is hence anisotropic, but the anisotropism is so weak that the mineral often appears isotropic: bixbyite is cubic, and should be isotropic, but often shows faint anisotropism. Bixbyite shows a greater tendency to form crystals than braunite, but this feature cannot be used as diagnostic. I have noticed that bixbyite is slightly yellower than braunite, especially in oil immersion, but again this feature is only of value when both minerals occur in the same section. It is likely that many braunite ores also contain bixbyite, and the presence of bixbyite may account for the low percentage of silica shown by some analyses of braunite, for example, that of braunite from Minas Geraes published by Ježek (48), with only 3.93 % $SiO_2$.

The only studies on the relation between braunite and bixbyite (sitaparite) in polished sections of manganese ores are those of Schneiderhöhn on the ores of Postmasburg in South Africa (94) and of Dunn on the Indian (Sitapar) ores (20). Schneiderhöhn evidently considered that braunite was pure $Mn_2O_3$ whereas bixbyite was $(Mn. Fe)_2O_3$. He was of the opinion that the bixbyite in these ores was younger than the braunite, that it represented a higher stage of metamorphism, and that it was formed by reaction between braunite and hematite, according to the equation

$$\begin{array}{l} Mn \cdot MnO_3 + Fe_2O_3 \rightarrow (Mn, Fe)MnO_3 \\ \text{braunite} + \text{hematite} \rightarrow \text{bixbyite} \end{array}$$

Unfortunately chemical analyses of the minerals and ores of Postmasburg to check the above reaction are not available. The essential difference between braunite and bixbyite lies not in the content of iron, but in the presence of 10 % $SiO_2$ in the braunite. There is no evidence in Schneiderhöhn's paper as to the fate of this silica in the transformation of braunite to bixbyite. Schneiderhöhn's description and his photographs of the polished sections certainly support the theory that bixbyite has been formed by reaction between braunite and hematite, but if so, the reaction must be more complicated than is indicated by his equation. I have attempted to carry out this reaction in the laboratory, by heating a mixture of finely powdered braunite and $Fe_2O_3$ in a furnace at 900° for twelve hours, but the two substances were without effect on each other under these conditions.

Dunn found that at Sitapar the braunite was to a large part definitely later than the bixbyite (sitaparite), veining and replacing it. In some specimens, however, the structure appeared to be a simultaneous intergrowth of the two minerals. Since the replacement of bixbyite by braunite is the opposite to the replacement observed by Schneiderhöhn in the Postmasburg ores, Dunn considered the possibility of retrogressive metamorphism, and searched for the hematite which should be formed according to Schneiderhöhn's equation. He found none, but remarks that the $Fe_2O_3$ set free might possibly have been absorbed by other minerals.

In a couple of polished sections of manganese oxide minerals from Långban I have observed bixbyite and braunite occurring together. Here, however, the structure does not indicate replacement of one mineral by the other; the bixbyite and the braunite appear to have crystallized contemporaneously. My interpretation is that in this case the mineral-depositing medium contained only a limited amount of silica, insufficient for all the manganese oxide to form braunite, hence the simultaneous formation of both bixbyite and braunite. At Långban braunite is the important ore-mineral, bixbyite being uncommon, if not rare. Probably the original manganese deposit which through metamorphism has given rise to the Långban ore-body was sufficiently siliceous for the conversion of all the original manganese oxide to braunite; bixbyite occurs in small amounts quite locally as a result of later processes of circulation and concentration.

## The system $MnO$-$Mn_2O_3$

No systematic study has yet been made on the system $MnO$-$Mn_2O_3$. This is no doubt due to its relative unimportance practically, and also to the difficulties attached to such an investigation on these refractory oxides. Whereas a knowledge of the phase relations of the oxides of iron is of vital importance not only for an understanding of the nature of iron ores but also of the problems involved in smelting these ores, the phase relations in the system $MnO$-$Mn_2O_3$ have not been seriously studied, since these oxides are not common ores of manganese, nor do they (excepting MnO) play any part in smelting processes.

Because of this, the data which we have on the system $MnO$-$Mn_2O_3$ are largely isolated facts, only too often contradictory, occurring in publications in which the study of the phase relations was not the primary object. On this account, and also because of the insufficiency of the material, no attempt will be made to draw up a phase diagram similar to that given for the system $FeO$-$Fe_2O_3$. In any case, a complete phase diagram is hardly necessary when considering the mineralogical aspects of the system $MnO$-$Mn_2O_3$, as the melting points of these oxides and the temperatures of the various solid-liquid equilibria in question lie far above the temperatures which have prevailed during the formation of those deposits which contain these oxides as minerals. On the other hand, the question of the miscibility of these oxides in the solid state is of importance in the consideration of deposits where they occur together.

In this connection there have been two laboratory studies, the results of which have a bearing on this question. Simon and Fehér (97), on the basis of measurements of the dissociation pressures of the different oxides, concluded that both $Mn_2O_3$ and $Mn_3O_4$ and $Mn_3O_4$ and $MnO$ formed mixed crystals. Le Blanc and Wehner (52), however, who applied quite a different procedure (the addition of oxygen to specially reactive MnO under determined conditions and the control of the products by chemical analysis and X-ray examination) came to quite the opposite conclusion. They state, and their results support the statement, that extensive solid solution of these oxides in each other is improbable. They found that from MnO to $MnO_{1.10}$ powder photographs showed only the lines of MnO; from $MnO_{1.10}$ to $MnO_{1.29}$ the lines of both MnO and $Mn_3O_4$ were visible; and from $MnO_{1.30}$ to $MnO_{1.40}$ only the lines of $Mn_3O_4$ were to be seen. They give no information as to the sensitiveness of this method, i. e. the least amount of one oxide in another which can be seen by the characteristic lines in a powder photograph, so, for example, the absence of lines of $Mn_3O_4$ in a sample corresponding to the formula $MnO_{1.10}$ is no evidence that this phase was not present in small amount. The most noteworthy feature of Le Blanc and Wehner's results is that the lattice dimensions of the different phases vary but little from one sample to another, and the variation is in no way systematic, as it should be if solid solution occurred. These results are supported by those of Dubois (19), who prepared the manganese oxides in many different ways but did not obtain any phases intermediate between MnO and $Mn_3O_4$, or between $Mn_3O_4$ and $Mn_2O_3$. For these reasons it may confidently be said that at the most solid solution plays a very minor and unimportant role in the mutual relations of MnO and $Mn_3O_4$, and of $Mn_3O_4$ and $Mn_2O_3$. In considering the results of Simon and Fehér, it must be borne in mind that measurement of dissociation pressures is at best an uncertain method of investigating phase relations, especially where no control is made on the homogeneity of the products. The same method as was used by Simon and Fehér was earlier used by Sosman and Hostetter (98), when they investigated the system $Fe_3O_4$-$Fe_2O_3$ and came to the conclusion that these two oxides were completely miscible in the solid state, a conclusion that has since been shown to be completely erroneous.

I have not made any systematic study on the phase relations in the system $MnO$-$Mn_2O_3$, but incidentally during the course of some experiments on the preparation of these oxides substances were obtained with composition lying between the compositions of the known oxides. From powder photographs all these substances were found to be inhomogeneous, being mechanical mixtures of two of the known oxides. These results are thus in agreement with those of Le Blanc and Wehner. The study of the occurrence of these manganese oxides as minerals has also shown that mutual solid solution has no observable influence on the relations between them in nature. For material for these studies I have been confined to specimens from Långban, as this is the only locality where the three oxides $MnO$, $Mn_3O_4$, and $Mn_2O_3$ occur in the same deposit. The relationships between manganosite, hausmannite, and braunite (which for the purpose of this discussion may be considered as a variety of $Mn_2O_3$) have been thoroughly described by Magnusson in his monograph on the Långban ore-body (55), and I have nothing to add to his description. Magnusson observed that hausmannite and manganosite often occurred together, and that in such an association manganosite occurred as cores in grains of hausmannite, suggesting that the hausmannite had been formed from manganosite by a process of oxidation. Where braunite and hausmannite occur together, the hausmannite has replaced the braunite, just as magnetite replaces hematite in the Långban iron ores. The cause is evidently the same in both cases, and is to be sought in a metamorphic process which had a reducing action upon the higher oxides, perhaps in connection with reducing fluids originating from magmatic sources. It was found by experiment during this investigation that braunite is easily reduced by hydrogen at 800°, the products being $MnO$ and $Mn_2SiO_4$. Less energetic reduction would presumably lead to the formation of $Mn_3O_4$ instead of $MnO$. The replacement of braunite by hausmannite must result in the setting-free of $SiO_2$, and the question arises as to the ultimate fate of this silica. At Långban it appears to have been absorbed in the formation of silicates such as manganese pyroxenes, amphiboles, olivines and micas.

Since at Långban braunite is replaced by hausmannite it is to be expected that bixbyite should also be replaced by hausmannite. Bixbyite is much rarer than braunite, so the chances of observing such a replacement are rather small, but I have seen it in a couple of specimens. These specimens showed crystals of bixbyite and braunite occurring together in a manganophyllite-calcite rock, and my attention was drawn to them by the bixbyite crystals being larger and less lustrous than usual, and showing a well-developed parting, a feature which is not typical of bixbyite. Polished sections of these specimens showed that the bixbyite had been largely replaced by a fine-grained hausmannite, so fine-grained indeed that it was difficult to identify in the microscope. The identification was checked, however, by a powder photograph of material bored from the section; the powder photograph showed the lines both of the bixbyite and the hausmannite. Thus bixbyite is also readily affected by a reducing environment and is then converted into hausmannite; indeed, it seems to be even more readily replaced under such conditions than braunite, as hausmannite replacement had apparently not affected the braunite crystals in the same section.

## The system FeO – MnO.

From the purely mineralogical viewpoint the system FeO-MnO is of little interest. FeO, or rather wüstite, is not known as a mineral, and MnO, manganosite, is extremely rare, and it is thus evident that the chances of finding substances belonging to this system in nature are very small. However, this system is of great importance in the study of the mineralogy of slags and of slag inclusions in iron and steel, as these oxides play a significant part in smelting processes. A short discussion of the principal features is therefore not out of place here.

For the first it must be emphasised that the system FeO-MnO is only quasi-binary, since FeO does not exist as such, but as the phase wüstite, which always contains more oxygen than corresponds to FeO; moreover wüstite disintegrates into Fe and $Fe_3O_4$ below 575°. This system is therefore more correctly regarded as a section of the ternary system Fe-Mn-O. However, it is simpler to deal with it as a binary system of FeO and MnO, and qualitatively this procedure probably does not lead to serious error. This procedure is also necessary in order to interpret the results of those who have investigated this system, as none of them have taken the above factors into account.

All the investigations on the system FeO-MnO have been made by workers interested in slags and slag systems. On one point only is there general agreement: all mixtures of FeO and MnO are completely miscible in the liquid state. Apart from that there is much discordance between the different investigators, essentially as to whether or not there is complete miscibility in the solid state also. Fig. 4 presents the different viewpoints. Hay and co-workers (37) gave a phase diagram similar in principle to that earlier proposed by Benedicks and Löfquist (6),

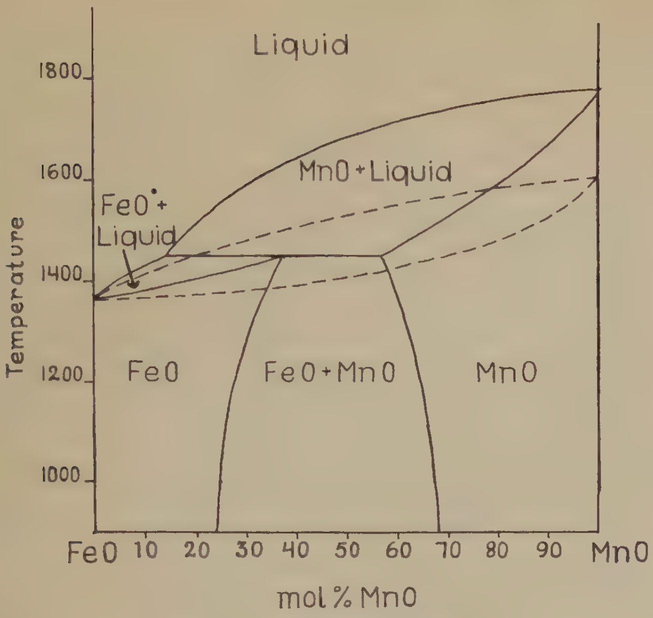


Figure 4. The system FeO-MnO.
– ——— Hay & co-workers (37); ———— Herty (39).

showing a region of immiscibility in the solid state. Herty (39), and later Andrew and co-workers (3). published essentially identical phase diagrams, and state that FeO and MnO are completely miscible both in the liquid and the solid state. I have not seen any description of the experimental work on which Herty based his conclusions, but Andrew and co-workers constructed their phase diagram on the basis of heating and cooling curves. Their photographs of polished sections of the specimens used for the heating and cooling experiments, however, hardly support their statement that there is complete miscibility in the solid state. Most of the specimens containing both FeO and MnO appear to show two phases, often very clearly, and one of their photographs (of a specimen containing 50 % FeO, 50 % MnO) shows a typical exsolution structure with lamellae of one phase oriented along the crystallographic directions in the other.[1] In addition, they claim to have prepared a homogeneous product containing 99.5 % FeO by decomposition of ferrous oxalate, a claim which is opposed by all investigations on the stability limits of the wüstite phase. Serious objections can therefore be raised to the statements of Andrew and his co-workers, and it must be considered doubtful if their representation of the FeO-MnO system is reliable. Hay and co-workers also used the method of heating and cooling curves for determining the phase boundaries, but in addition they determined the homogeneity or otherwise of their samples by optical examination, finding that in samples with between 20—50 % MnO two phases were present in the solid state. They also determined the lattice dimensions of the pure oxides by means of powder photographs, but omitted to do the same for their intermediate phases.

---

[1] A statement by Herty (39, p. 4) that when steel was deoxidized by the addition of manganese, typical globules (of oxide) were encountered, some of which showed at least two phases, also conflicts with his diagram showing complete miscibility of MnO and FeO in the solid state.

Taking all the evidence into consideration it appears most likely that in this system there is a region of immiscibility in the solid state. This was the opinion of Benedicks and Löfquist, and of Hay and his co-workers, and a recent investigation of this system by Grieve and White (33) is apparently in agreement, although I have not seen their paper other than in the form of a short abstract. My own experience of this system is limited to an investigation of the mineralogy of some slags from the basic open-hearth process. In general these slags contained too little manganese and too much magnesium for the oxide phase to be considered as belonging to the FeO-MnO system. One slag, however, was exceptionally rich in manganese, and it was possible to extract the oxide phase in a rather pure state from the powdered slag by the use of Clerici solution. The separated oxide was analysed and found to consist largely of FeO and MnO in the proportion of 2 : 3, with only a little CaO and MgO in solid solution. A powder photograph of this oxide phase showed that it consisted of one phase only, with a cell edge of 4.36 A, approximately midway between that of FeO and that of MnO. Polished sections of this slag also showed that the oxide phase was homogeneous. At first sight this result might appear contrary to the evidence for incomplete miscibility of FeO and MnO in the solid state. However, the composition of this one oxide phase appears to fall outside the two phase region; also the rate of cooling of the slag was probably so great that the homogeneous FeO-MnO liquid did not have time to unmix in the solid state, even if it should theoretically have done so. It is likely that statements on the complete miscibility of FeO and MnO in the solid state are based on the examination of specimens which were actually in a metastable state, the conditions of cooling having been such that unmixing could not take place. Such a relation is certainly true for the rather similar system MnO-MgO, where synthetic studies fixed a much more extensive miscibility in the solid state than actually holds good at ordinary temperatures (Frondel, 28).

## The system $Fe_3O_4 - Mn_3O_4$.

Of all the binary systems within the scope of this paper the system $Fe_3O_4$-$Mn_3O_4$ is probably the most interesting, both from physicochemical and mineralogical viewpoints: physicochemically because of the structural relationship between $Fe_3O_4$, which has a cubic lattice of the spinel type, and $Mn_3O_4$, with a tetragonal lattice which can, however, be looked upon as a deformed spinel lattice; mineralogically because so many minerals have been described whose composition shows that they belong to this system — magnetite, manganmagnetite, manganomagnetite, jacobsite, vredenburgite, hausmannite. It is therefore surprising to find that our knowledge of the quantitative relations in this system is extremely limited. In the literature I have not found any attempt to draw up a phase diagram for the system, nor have any composition limits for the different mineral species been proposed.

In order to investigate the phase relations in this system a series of preparations were made covering systematically all compositions between $Fe_3O_4$ and $Mn_3O_4$ at intervals of 10 mol% and occasionally also at 5 mol%. These preparations were made in the following way: manganous sulphate and ferrous sulphate were weighed out in the desired proportions and dissolved in hot water, the solution precipitated by means of a small excess of sodium hydroxide solution, the precipitate of hydroxides washed first by decantation and then on a filter until free from sulphate, and dried by heating in an oven with free access of air at 165° for 24 hours. The products thus obtained were converted to $(Fe, Mn)_3O_4$ by heating in an electric furnace at 1150°—1300° for periods varying from 12 to 20 hours. Under these conditions it was possible to obtain homogeneous preparations covering the range from 20—100 % $Mn_3O_4$.[1] Syntheses containing less than 20 % $Mn_3O_4$ could not be prepared in this way without exceeding 1300°, beyond the capacity of the furnaces available.

The phase relations in these products were investigated by means of powder photographs. All the products were found to consist of one phase only, indicating that $Fe_3O_4$ and $Mn_3O_4$ are completely miscible in the solid state at about 1200°. The variation of lattice dimensions with composition is given in Fig. 5. With increasing amount of manganese in solid solution the lattice dimensions increase steadily from 8.38 A for pure $Fe_3O_4$ to a limit of 8.51 A at about 60 % $Mn_3O_4$. At that point

---

[1] In order to control that the composition of the products corresponded to the amounts of manganous and ferrous sulphate taken, the percentages of iron in some of the samples were confirmed by chemical analysis (by Dr. Naima Sahlbom).

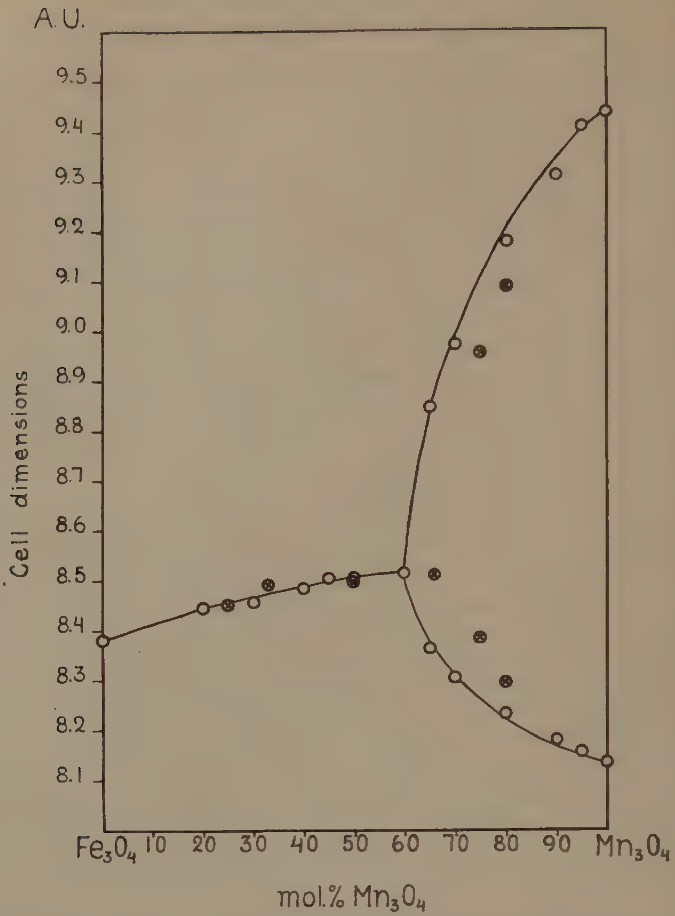


Figure 5. The variation of lattice dimensions with composition in the system $Fe_3O_4—Mn_3O_4$.

○ present investigation; ⊗ Montoro (66).

the cubic lattice is not longer stable, and becomes deformed into a tetragonal lattice, the ratio $c/a$ increasing continuously from 1 at 60% $Mn_3O_4$ to 1.16 at 100 % $Mn_3O_4$. The length of the $a$ axis decreases to 8.14 A, that of the $c$ axis increases to 9.43 A. The volume of the unit cell increases from 588 A³ for pure $Fe_3O_4$ to 625 A³ for $Mn_3O_4$ (Fig. 6).

It is evident that the replacement of iron by the larger manganese atoms results in an increase in size of the unit cell. Probably also it is the size or a certain asymmetry of the manganese atoms which causes the deformation of the cubic cell to a tetragonal one. Thus $ZnMn_2O_4$

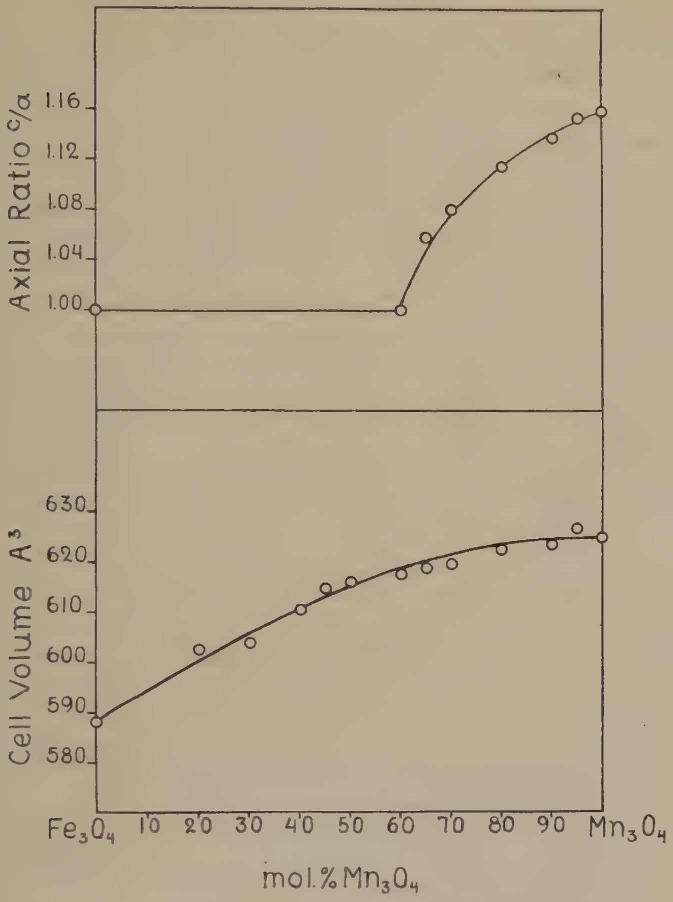


Figure 6. The variation in cell volume and axial ratio in the system $Fe_3O_4—Mn_3O_4$.

has the same tetragonal structure as $Mn_3O_4$, although all other zinc spinels are cubic. It is evident that the limit of stability of the spinel structure in general lies at an ionic size close to that of manganese, as slightly larger ions, such as calcium, do not form compounds of the spinel type.

This apparently continuous change from a structure with cubic symmetry to one with tetragonal symmetry is at first sight rather startling. Only two other examples of such a change are known to me, the copper-manganese system described by Persson (80) and the iron-manganese system described by Öhman (73), in which copper and iron (cubic) form a complete series of solid solutions with manganese (tetragonal).

Both Persson and Öhman reckoned with the possibility that the transition from cubic to tetragonal symmetry was a discontinuous process. Although in spite of much effort they were unable to show the occurrence of any two-phase region separating the cubic and tetragonal phases, they introduced into their phase diagrams a very limited conjectural two-phase area, in order to show the possibility of a discontinuity. It is perhaps difficult to conceive of a continuous transition from cubic to tetragonal symmetry, since such a lowering of symmetry in itself implies a discontinuity. Even the relatively slight change in symmetry from high to low quartz is not a continuous process. The curves showing the variation of refractive indices of the two forms approach each other towards the transition point, but they do not meet.

The system $Fe_3O_4$-$Mn_3O_4$ is quite similar to the systems Fe-Mn and Cu-Mn as far as the transition from a cubic to a tetragonal lattice is concerned. My observations are that a preparation containing 60 % $Mn_3O_4$ has a cubic lattice, one with 65 % $Mn_3O_4$ a tetragonal lattice, and that from the curves showing the change of lattice dimensions with composition there appears to be a continuous transition between the two. If there is a two-phase area separating them I have not been able to observe it, and it must in any case be very limited. In the range between 60 % and 70 % $Mn_3O_4$ it is difficult to make the preparations homogeneous, and the lines in the powder photographs are more diffuse than usual, but these powder photographs showed no lines that could not be interpreted as lines of the tetragonal lattice. The volume of the unit cell also appears to increase continuously in spite of the transition from the cubic to the tetragonal lattice. As will be described later, the curve of the variation of magnetic susceptibility with composition shows a slight arrest between 60 % and 70 % $Mn_3O_4$, but I am not convinced that this arrest is significant, as it can be due to other factors, such as experimental error, or degree of packing of the preparation when the determination was made. On the whole, I believe on the evidence available that in the system $Fe_3O_4$-$Mn_3O_4$ there is a continuous transition from a cubic to a tetragonal lattice, but I do not deny that weighty considerations can be advanced for the improbability of such a transition.

Apart from isolated determinations on the lattice dimensions of the so-called manganoferrite, $MnFe_2O_4$, the only investigation of the system $Fe_3O_4$-$Mn_3O_4$ by X-ray methods is that of Montoro (66). He made synthetic preparations covering the range from $Fe_3O_4$ to $Mn_3O_4$ by the same method as I employed, and measured their lattice dimensions from powder photographs. His determinations are plotted on Fig. 5, and it can be seen that on the whole they are in reasonable agreement with my own figures. He also found a continuous transition from a cubic to a tetragonal lattice, but he placed the transition point at 66.7 % $Mn_3O_4$, somewhat higher than that found in this investigation. Montoro believed that this transition point was linked with the formation of a ferrous manganite, $FeO \cdot Mn_2O_3$, which would have exactly the composition 66.7 % $Mn_3O_4$. His curve for the variation of lattice dimensions with composition also shows an irregularity at 33.3 % $Mn_3O_4$, which he ascribed to the presence of a compound $MnO \cdot Fe_2O_3$, manganous ferrite. I believe that this irregularity is more imaginary than real, being within the possible limit of error in determining the lattice dimensions. The existence of a definite compound $MnO \cdot Fe_2O_3$ is hardly more reasonable than the existence of a compound labradorite in the albite-anorthite series; both are simply artificial points in a solid solution series. The same is also true of the supposed ferrous manganite, $FeO \cdot Mn_2O_3$; more and better evidence is required for the existence of this compound than that advanced by Montoro, in particular, evidence that all the iron in it is divalent and all the manganese trivalent.

So far the only information that has been obtained towards building up a phase diagram for the $Fe_3O_4$-$Mn_3O_4$ system is that at 1200° the two oxides are completely miscible. The melting temperatures in this system are higher than could be investigated with the equipment available. However, the approximate form and position of the liquidus-solidus boundaries can be derived from melting-point determinations by other investigators. The melting point of $Fe_3O_4$ is 1591° (Greig and co-workers, 32); that of $Mn_3O_4$ 1565° (Wartenburg & Reusch, 118); and that of manganese ferrite, $MnFe_2O_4$, is 1570° (van Arkel and co-workers, 106). It is on the basis of this admittedly rather meagre data that the liquidus and solidus curves are drawn in the phase diagram (Fig. 7). Since, however, there is a considerable area of immiscibility of two phases at lower temperatures it is possible that future investigation will reveal a minimum on the solidus-liquidus curves between 60 % and 90 % $Mn_3O_4$, analogous to that present in other systems of this type.

The researches so far described and discussed give a picture of the phase relations in this system at high temperatures, but say nothing as to conditions at low temperatures. Since the solid solutions prepared at high temperatures show no signs of exsolution at ordinary temperatures, it might be thought that the miscibility of $Fe_3O_4$ and $Mn_2O_4$ is complete at all temperatures. It was first the examination of a specimen from Långban which revealed the presence of a region of immiscibility in this system and enabled the approximate limits of this re-

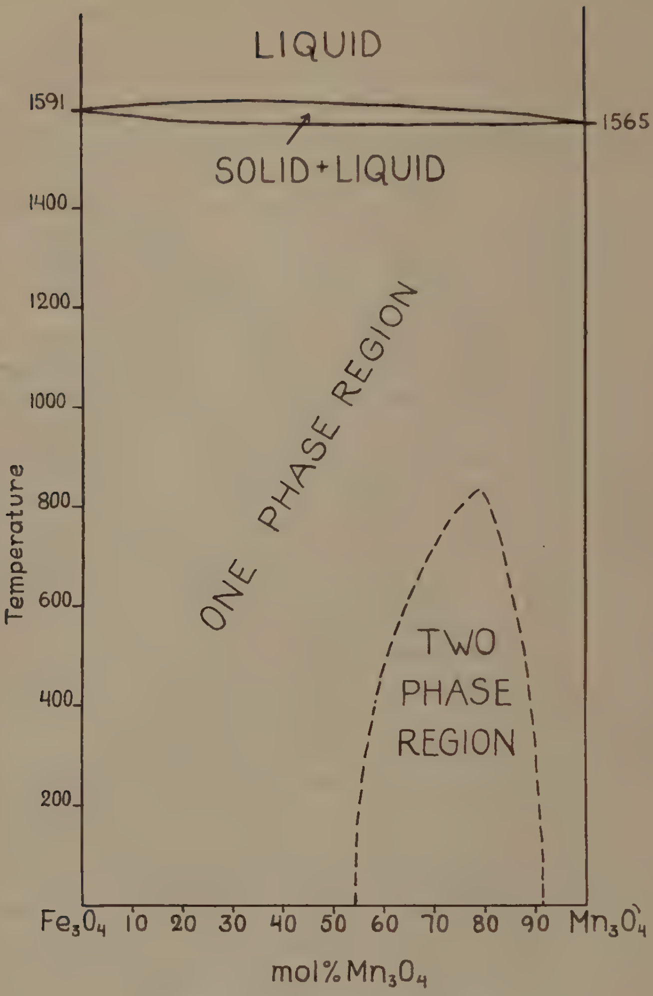


Figure 7. The system $Fe_3O_4$—$Mn_3O_4$.

gion to be fixed. This specimen, which by qualitative analysis was found to be an iron-manganese oxide, gave a powder photograph showing the presence of two phases, one of which was jacobsite, the other a tetragonal phase with structure as that of pure $Mn_3O_4$ but with different lattice dimensions and a lower axial ratio, evidently due to the presence of iron in solid solution. A polished section of the specimen showed a beautifully regular structure, lamellae of an anisotropic mineral (the tetragonal phase) being oriented along the octahedral planes of the isotropic groundmass (the jacobsite). It was then realized that the specimen was the mineral vredenburgite, described by Fermor in 1908 (21), and in 1931 shown to be an intergrowth of two listinct minerals, independently by Orcel and Pavlovitch (74) in France and Schneiderhöhn and Ramdohr (93) in Germany. Schneiderhöhn and Ramdohr identified the two minerals of the intergrowth as jacobsite and hausmannite, and pointed out that the structure was typical of exsolution on cooling of a mix-crystal formed at higher temperatures.

Thus in nature we find minerals which have reached a state of equiibrium which in general cannot be reproduced with laboratory products. The mineral intergrowth known as vredenburgite has evidently been formed as a homogeneous mix-crystal under conditions of elevated temperature and pressure. However, the return to normal temperature and pressure has proceeded sufficiently slowly for a continual readjustment to the new conditions, with the consequence that the natural mineral is in a state of equilibrium even under present conditions. Therefore the composition of the two phases making up vredenburgite represent the limiting values of the solubility of $Mn_3O_4$ in $Fe_3O_4$ and of $Fe_3O_4$ in $Mn_3O_4$ at normal temperatures and pressures.

Thus in order to determine the position of the limits of solid solution n the phase diagram of the system $Fe_3O_4$-$Mn_3O_4$ it is only necessary o determine the composition of each of the two phases in vredenburgite. It is not possible to do this directly, by separating the two phases and analysing them individually; the two phases are so intimately intergrown that no known method of separation would be ikely to give a pure concentrate of either or both of them. Under such circumstances recourse must be had to determining the chemical composition of the individual phases from the measurement of some physical property which shows a regular variation with composition. Since the powder photographs of the Långban vredenburgite showed the lines both of the cubic and the tetragonal phases it was a simple matter to determine the lattice dimensions of the two phases. For the cubic phase the cell edge $a$ was 8.50 A, for the tetragonal phase $a = 8.17$ A, $c = 9.35$ A, $c/a = 1.144$. Now from the lattice dimensions of laboratory products of known composition the curve correlating chemical composition with lattice dimensions in the $Fe_3O_4$-$Mn_3O_4$ system was obtained (Fig. 5). Conversely, from the lattice dimensions of a substance belonging to this system it is possible to read off from Fig. 5 the composition corresponding to these dimensions. Thus the lattice dimensions $a = 8.17$ A, $c = 9.35$ A correspond to a composition of 91 % $Mn_3O_4$, 9 % $Fe_3O_4$, and from the probable experimental error involved in the determinations the accuracy of the composition derived in this way can be put as ± 2 %.[1] The cell edge of the cubic phase, 8.50 A, corresponds to a composition of about 50 % $Fe_3O_4$, 50 % $Mn_3O_4$; here, unfortunately, the accuracy is not nearly so great, as between 40 % and 60 % $Mn_3O_4$ the lattice dimensions vary only slightly with composition. However, a lucky chance enabled the composition of the limiting cubic phase to be determined with as great an accuracy as for the tetragonal phase. A specimen of vredenburgite from Långban was found which consisted almost entirely of the cubic phase. A polished section showed only rare lamellae of the tetragonal phase, and its amount was insufficient to give the characteristic lines on powder photographs. The amount of the tetragonal phase present was estimated at 5 % or less. An analysis of the specimen gave $Mn_3O_4 = 55.9\%$. From these facts the limiting composition of the cubic phase could be placed at 54 % $Mn_3O_4$ with an accuracy of about ± 2 %.

The determination of the solubility limits of $Fe_3O_4$ in $Mn_3O_4$ and of $Mn_3O_4$ in $Fe_3O_4$ from the determination of the composition of the two phases in vredenburgite rests on the assumption — from previous discussions a reasonable assumption — that the vredenburgite is in a state of equilibrium. The correctness of this assumption cannot be directly proved, but is substantiated by the following argument. If the mineral vredenburgite represents a state of equilibrium in the system $Fe_2O_4$-$Mn_3O_4$, then all vredenburgites, whatever their origin and whatever their bulk composition within the immiscibility limits of the system, should consist of an oriented intergrowth of the cubic phase and the tetragonal phase, and the composition of these two phases should always be the same, variations in bulk composition being compensated by variation in the relative amounts of the two phases. Since the composition of the two phases should always be the same, the lattice dimensions of the two phases should also always be the same.

Thus this line of reasoning can be checked by the determination of the lattice dimensions of as many specimens of vredenburgite as possible. Such a check is not so easily carried out in practice, as vredenburgite is a comparatively rare mineral, on account of the special combination of circumstances necessary for its formation. It is confined to metamorphosed ore deposits containing both iron and manganese, and the only localities where it has been identified are the Långban and Jakobsberg mines in Sweden and several of the manganese mines in the metamorphic ore deposits of India. I have had material from all these localities and from powder photographs have determined the lattice dimensions of the phases present. The lattice dimensions of the tetragonal phase could not always be determined, either because it was present in insufficient quantity to give lines in the powder photographs, as in some Långban specimens, or because it had partly or wholly been replaced by pyrolusite and psilomelane, as was usual in the material from India. The results with different specimens are given in the following table.

---

[1] This figure for the limiting miscibility of $Fe_3O_4$ is confirmed by the finding a specimen of homogeneous hausmannite from Långban with 6.91 % $Fe_3O_4$; the lattice dimensions of this specimen were $a = 8.16$ A, $c = 9.35$ A, very close to those of the hausmannite in the vredenburgite intergrowth.

| | $a_{cub.}$ | $a_{tetr.}$ | $c_{tetr.}$ | $c/a_{tetr.}$ |
|---|---|---|---|---|
| Långban 1 | 8.50 | 8.17 | 9.35 | 1.144 |
| Långban 2 | 8.50 | — | — | — |
| Jakobsberg 1 | 8.50 | 8.16 | 9.34 | 1.145 |
| Jakobsberg 2 | 8.50 | 8.16 | 9.35 | 1.146 |
| Jakobsberg 3 | 8.49 | 8.15 | 9.34 | 1.146 |
| Kodur (India) 1 | 8.48 | 8.16 | 9.37 | 1.148 |
| Kodur 2 | 8.48 | 8.16 | 9.37 | 1.148 |
| Kodur 3 | 8.48 | 8.17 | 9.33 | 1.142 |

At first glance the constancy of the lattice dimensions, although reasonably good, is perhaps not so precise as might be demanded. However, two factors must be borne in mind when considering these figures. Firstly the possible experimental error in the determination of the lattice dimensions is ± 0.01 A, although in general I believe the accuracy is greater, perhaps ± 0.005 A, so that this factor is insufficient to fully explain the variation in the lattice dimensions of the two phases. The second factor, and the important one, is that these natural minerals rarely contain iron and manganese alone, but also other elements in solid solution, and these foreign elements naturally affect the lattice dimensions. The Långban specimens have proved to be practically pure $(Mn, Fe)_3O_4$, so that conclusions drawn from the investigation of these specimens can be directly applied to the elucidation of the system $Fe_3O_4$-$Mn_3O_4$. Both the Jakobsberg and the Indian vredenburgites, however, contain small amounts of other elements, the most important being magnesium, analyses showing 1 % or more MgO. Since magnesium atoms are smaller than those of iron and manganese, the presence of magnesium in solid solution will result in a lowering of the lattice dimensions of the two phases in vredenburgite, and this is evidently the explanation of the decrease in the lattice dimensions of the vredenburgites from Jakobsberg and Kodur in comparison with the lattice dimensions of the vredenburgite from Långban. When due allowance is made for this effect it is evident that the above figures do substantiate the assumption that these vredenburgites represent a system in equilibrium.

Thus from the investigation of vredenburgite it has been possible to show that at ordinary temperatures there is a considerable region of immiscibility in the $Fe_3O_4$-$Mn_3O_4$ system, extending from 54 % to 91 % $Mn_3O_4$. Since the miscibility of two phases generally increases with increasing temperature, this region of immiscibility must grow smaller at higher temperatures and at a sufficiently high temperature will disappear altogether; above this temperature only homogeneous solid solutions of $Fe_3O_4$ and $Mn_3O_4$ will be formed. This temperature must lie below 1200°, since all the artificial preparations which were made for the investigation of the $Fe_3O_4$-$Mn_3O_4$ system were homogeneous at this temperature. Natural vredenburgites become homogeneous also when heated for 24 hours at 1100° or higher. Attempts were made to determine the extent of the region of immiscibility in the phase diagram by heating the homogeneous laboratory preparations in evacuated tubes at different temperatures between 500° and 1000° (the evacuated tubes were necessary in order to prevent oxidation to the $R_2O_3$ oxide at these lower temperatures). Unfortunately the experimental results are not as complete as was hoped; it was found that at 700° and below no readjustment took place, even after heating the samples for three days, so that at these temperatures no information was obtained. At 750° the samples with 10 %, 30 %, and 35 % $Mn_3O_4$ were still homogeneous, but the sample with 20 % $Mn_3O_4$ had disintegrated into two phases; the lattice dimensions of one phase were $a = 8.19$ A, $c = 9.28$ A, corresponding to 16 % $Mn_3O_4$, the lattice dimensions of the second phase were $a = 8.28$ A, $c = 9.03$ A, corresponding to 28 % $Mn_3O_4$. At 950° all the samples remained completely homogeneous; the culminating point of the region of immiscibility must therefore lie below this temperature. It is on the basis of this rather meagre data that the curve bounding the region of immiscibility in Fig. 7 has been drawn. It is somewhat asymmetrical in the direction of $Mn_3O_4$, and its culminating point lies between 800° and 900°. The curve is drawn in broken lines, to indicate that it is somewhat conjectural, although I believe that it is at least qualitatively correct.

An important feature of the $Fe_3O_4$-$Mn_3O_4$ system is the occurrence of ferromagnetism. $Fe_3O_4$ is strongly ferromagnetic, $Mn_3O_4$ is paramagnetic, but little has hitherto been known concerning the magnetic properties of intermediate substances. Jacobsite is as strongly attracted by a magnet as magnetite, whereas hausmannite is completely indifferent. Vredenburgite is as magnetic as magnetite, on account of the jacobsite present in it. Evidently the change from paramagnetic to ferromagnetic lies in the region between pure $Mn_3O_4$ and 54 % $Mn_3O_4$, 46 % $Fe_3O_4$. In order to determine the nature of this change measurements of magnetic susceptibility were made on the synthetic preparations containing from 0—55 % $Fe_3O_4$ in solid solution with $Mn_3O_4$. These measurements

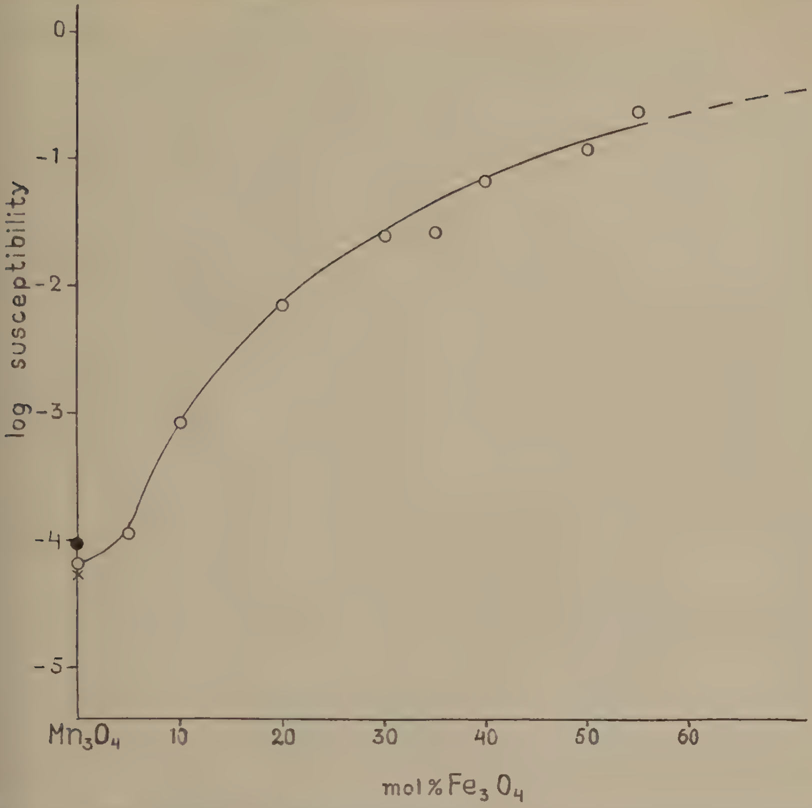


Figure 8. The variation of specific susceptibility with composition in the system $Fe_3O_4-Mn_3O_4$.
× Wedekind & Horst (119); ● Deb (16).

were made with a magnetometer built by Sture Werner of the Swedish Geological Survey and with his assistance, and I would like to express my thanks for this help. The results are expressed in Fig. 8, which shows the variation of the specific susceptibility with composition. The curve is a continuous one, the susceptibility increasing with increase in $Fe_3O_4$. Thus it can be said that the degree of magnetism is a function of the content of $Fe_3O_4$. Considering the individual determinations, Fig. 8 shows that there is possibly a slight arrest between 30 % and 40 % $Fe_3O_4$, as the preparation with 35 % $Fe_3O_4$ gave almost the same value for the specific susceptibility as the preparation with 30 % $Fe_3O_4$. I am not convinced, however, that this arrest is significant, because the material used in this determination underwent a somewhat different heat treatment during its preparation, being calcined at a temperature about 100° above that used for the others. The same is true for the sample with 55 % $Fe_3O_4$, which also falls slightly off the smooth curve.

There is very little published data on the magnetic susceptibilities of these manganese-iron oxides. Wedekind and Horst (119) determined the susceptibility of artificial $Mn_3O_4$ and found it to be $65.5 \times 10^{-6}$ cgs units. Deb (16) has measured the susceptibility of hausmannite from Thuringia and found a value of the order of $95 \times 10^{-6}$ cgs units. These values are plotted on Fig. 8 and are in reasonably good agreement with the results obtained in this investigation. Deb also determined the susceptibility of a specimen of jacobsite from Sweden (probably from Jakobsberg) and found that it was greater than $85\,000 \times 10^{-6}$ cgs units. The composition of the jacobsite was not determined, but from Fig. 8 the susceptibility lies on that part of the curve at about 50 % and greater of $Fe_3O_4$. The susceptibility of jacobsite is evidently much the same as that of magnetite, and the degree of ferromagnetism first begins to decrease rapidly below a content of 40 % $Fe_3O_4$.

Having determined the main features of the phase diagram, it is now possible to make a rational survey of the mineral species comprised within the system $Fe_3O_4$-$Mn_3O_4$, and to fix definite limits for their composition. Leaving out redundant names, there are four reasonably well established species in this system: magnetite, jacobsite, vredenburgite, and hausmannite. The composition limits of hausmannite and vredenburgite are readily and unambiguously fixed from the phase diagram. Vredenburgite signifies those substances whose composition lies within the area of immiscibility, i. e. between 54 % and 91 % $Mn_3O_4$. Vredenburgite cannot be considered as an individual species in the strict sense, as it is an oriented intergrowth of two distinct species, jacobsite and hausmannite. However, it is clearly necessary to have a name to designate such an intergrowth, just as the name titanomagnetite is accepted for the oriented intergrowths of ilmenite in magnetite which are also a result of exsolution. All vredenburgites so far described show the typical oriented intergrowth of jacobsite and hausmannite, but it is conceivable that specimens may be found in which exsolution has not taken place, and which would therefore be completely homogeneous, just as the homogeneous titanomagnetites which are not uncommon in lavas. I believe that I have observed such a homogeneous vredenburgite in a polished section of a specimen from Långban, but have yet to obtain definite proof; unfortunately it occurs so intimately mixed with bixbyite that it is impossible to extract it for analysis.[1] The properties of such an undissociated vredenburgite are closely similar to those of hausmannite and it might easily be classed as hausmannite, but if its composition lies between 54 % and 91 % $Mn_3O_4$ it should be classed as vredenburgite, possibly with some distinguishing prefix such as $\alpha$-vredenburgite, $\beta$-vredenburgite signifying unmixed vredenburgite.

---

[1] The evidence for this specimen containing a homogeneous vredenburgite is in the powder photographs. These show the lines corresponding to two phases, one being bixbyite, the other a tetragonal $(Mn, Fe)_3O_4$ phase with $a = 8.25$ A, $c = 9.09$ A, equivalent, from Fig. 5, to a composition $Mn_3O_4 = 75$ %, $Fe_3O_4 = 25$ %, within the vredenburgite field.

The upper limit of the area of immiscibility in the $Fe_3O_4$-$Mn_3O_4$ system lying at 91 % $Mn_3O_4$, it follows that between 91—100 % $Mn_3O_4$ only homogeneous crystals occur. Thus the term hausmannite covers $Mn_3O_4$ with up to 9 % $Fe_3O_4$ in solid solution. From the analyses of hausmannite which have been published, it appears that this mineral generally occurs as practically pure $Mn_3O_4$, with little or no substitution of manganese by other elements. This is presumably due to lack of opportunity rather than to lack of ability to accomodate foreign elements in its space lattice. At Långban, which is probably the greatest deposit of hausmannite known, the mining engineers have tacitly assumed that the hausmannite itself is completely iron-free, and are occasionally troubled by the appearance of several percent of $Fe_3O_4$ in the hausmannite concentrate. When visiting the mine in the summer of 1942 I took the opportunity of collecting specimens from selected places in the ore-body, and found that although the hausmannite usually was so free from iron that it failed to give the thiocyanate test, occasionally it gave a strong positive reaction to this test. The cause was not far to seek; the specimens of hausmannite which gave a strong positive reaction all came from parts of the mine where the manganese and iron ore-bodies, usually well separated, approached each other, and a transference of material had evidently taken place.

The limits of the species vredenburgite and hausmannite are clearly fixed by bounding curves in the phase diagram. Not so, however, are the limits of magnetite and jacobsite. The lower limit of magnetite is obviously fixed at 0 % $Mn_3O_4$, the upper limit of jacobsite at 54 % $Mn_3O_4$. But where shall the boundary between jacobsite and magnetite be drawn? Jacobsite has generally been considered as manganese ferrite, $MnFe_2O_4$, but it has yet to be proved that this is an actual compound of one molecule of MnO with one molecule of $Fe_2O_3$ and not just a point in a continuous series of solid solutions of $Mn_3O_4$ in $Fe_3O_4$. None of the published analyses of jacobsite corresponds to the theoretical $MnFe_2O_4$. From a purely structural standpoint there are no grounds for differentiating between magnetite and jacobsite, and any definite boundary drawn between them must be an artificial and arbitrary one. Nevertheless such a boundary must be drawn; jacobsite and magnetite have long been accepted as distinct minerals, and no good purpose would be served by attempting to unite them as a single species. Besides, apart altogether from chemical tests, the two minerals can be distinguished

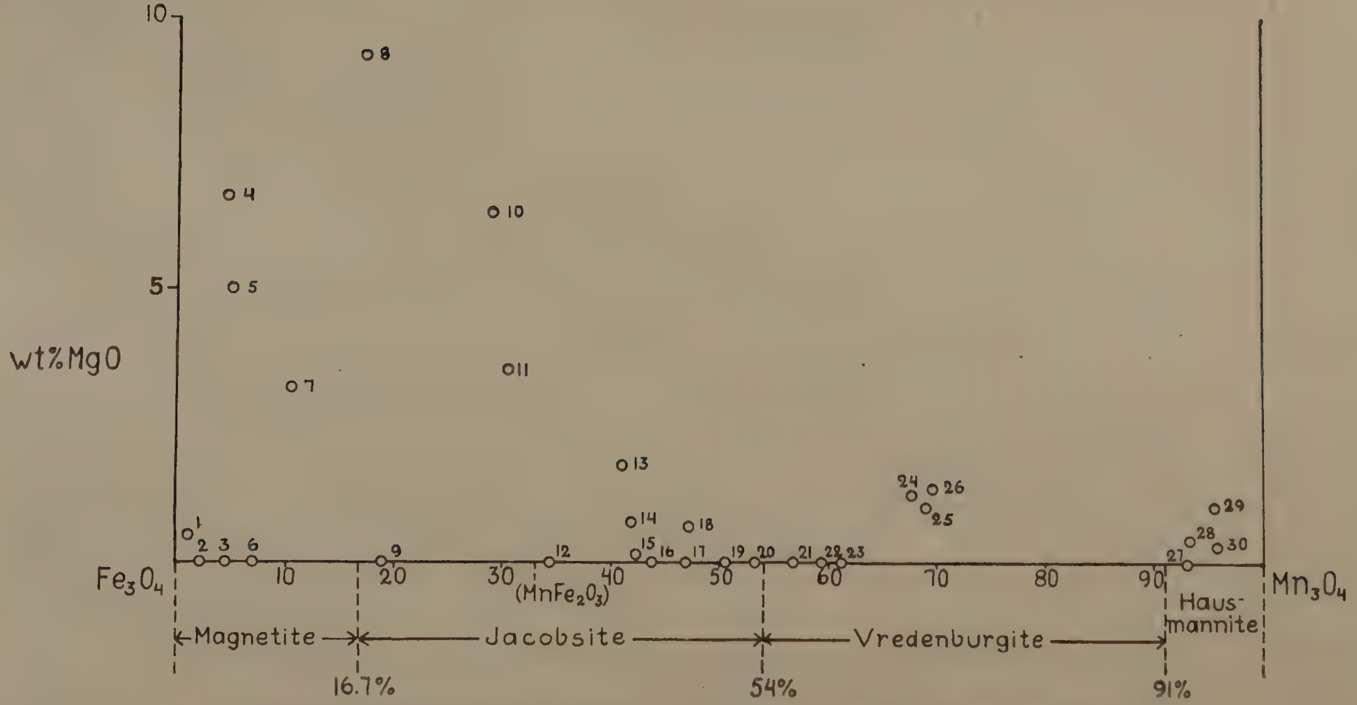


Figure 9. Composition diagram for analyses of minerals in the system $Fe_3O_4$—$Mn_3O_4$.

— often of course only with much difficulty — by the differences in physical properties. The streak of magnetite is black, that of jacobsite dark brown; the specific gravity of jacobsite is slightly but distinctly lower than that of magnetite; in polished sections jacobsite shows an olive tinge which serves to distinguish it from magnetite, and sometimes has dark red inner reflections, something never found in magnetite. With powder photographs it is not difficult to distinguish the two minerals, as the lattice dimensions of jacobsite are considerably higher than those of magnetite. However, there is in any case a complete transition between the two minerals, and wherever the boundary between them is drawn, those specimens whose composition falls close to this boundary will have to be named from their chemical composition alone. The problem is further complicated by the common presence of magnesium in solid solution in jacobsites, and from published analyses there exists a continuous transition from jacobsite to magnesioferrite. After much consideration I believe that the most satisfactory solution is to call jacobsite all those specimens in which the theoretical manganoferrite molecule, $MnFe_2O_4$, is the dominant one. In the $Fe_3O_4$-$Mn_3O_4$ system $MnFe_2O_4$ corresponds to 33.3 % $Mn_3O_4$. Therefore the boundary between jacobsite and magnetite will lie at a composition corresponding to 50 %

---

1. Magnetite, Tongue, Scotland. Mineralog. Mag., 5, 150, 1884.
2. » Arendal, Norway. Jahrb. Chem., 8, 429, 1832.
3. » Väster Silvberg, Sweden. Mineralog. petrog. Mitt., 7, 110, 1886.
4. » Schelingen, Germany. Neues Jahrb. Mineral. Geol., I, 200, 1913.
5. » New Zealand. Mineralog. Mag., 8, 123, 1889.
6. » Väster Silvberg, Sweden. Mineralog. petrog. Mitt., 7, 110, 1886.
7. » St. Joseph du Lac, Quebec. Mineralog. Mag., 14, 373, 1907.
8. Jacobsite, Jakobsberg, Sweden. Z. Krist., 68, 108, 1928.
9. » Siegen, Germany. Rammelsberg, Mineral.-Chem., 132, 1875.
10. » Jakobsberg, Sweden. Compt. rend., 69, 170, 1869.
11. » Debarstica, Bulgaria. Z. Kryst, 36, 202, 1902.
12. » Nordmarken, Sweden. Bull. soc. franç. minéral., 10, 185, 1887.
13. » Långban, Sweden. Geol. Fören. Förh., 3, 384, 1876—77.
14. » Glakärn, Sweden. Geol. Fören. Förh., 12, 138, 1890.
15. » Beldongri, India. Trans. Nat. Inst. Sci. India, 1, 108, 1936 (No. 779a).
16. » Sjögruvan, Sweden. Bull. soc. franç. minéral., 10, 172, 1887.
17. » Sjögruvan, Sweden. Bull. soc. franç. minéral., 10, 173, 1887.
18. » Beldongri, India. Trans. Nat. Inst. Sci. India, 1, 108, 1936 (No. 779b).
19. » Beldongri, India. Records Mysore Geol. Dept., 34, 82, 1935 (No. 1).
20. » Sjögruvan, Sweden. Bull. soc. franç. minéral., 10, 173, 1887.
21. Vredenburgite (Manganomagnetite), Långban, Sweden. Bihang till Kgl. Svenska Vetenskapsakad. Handl., 12, part II, no. 2, 27, 1886.
22. » Devada, India. Records Mysore Geol. Dept., 34, 82, 1935 (No. 2).
23. » Kodur, India. Records Mysore Geol. Dept., 34, 82, 1935 (No. 3)
24. » Garividi, India. Mem. Geol. Survey India, 37, 44, 1909.
25. » Beldongri, India. » » » » » » »
26. » Jakobsberg, Sweden. Z. Krist., 68, 116, 1928.
27. Hausmannite, Långban, Sweden. Analysed Anna-Greta Hybbinette, 1943.
28. » Jakobsberg, Sweden. Bull. soc. chim., (3) 29, 1110, 1903.
29. » Långban, Sweden. Bull. soc. chim., (3) 29, 1110, 1903.
30. » » » » » » » » »

$MnFe_2O_4$, 50 % $Fe_3O_4$, i. e. at 16.7 % $Mn_3O_4$. The upper limit of jacobsite is naturally fixed by the boundary against vredenburgite at 54 % $Mn_3O_4$. Therefore by the above convention jacobsite is defined as including all those specimens of $(Fe, Mn)_3O_4$ containing between 16.7 and 54 % $Mn_3O_4$. Where foreign elements, such as magnesium, are present in solid solution the name jacobsite is the valid one when the molecule $MnFe_2O_4$ is dominant.

The system $Fe_3O_4$-$Mn_3O_4$ has thus been divided up into four mineral species according to the following scheme: magnetite, from 0—16.7% $Mn_3O_4$; jacobsite, from 16.7—54 % $Mn_3O_4$; vredenburgite, from 54—91 % $Mn_3O_4$; and hausmannite, from 91—100 % $Mn_3O_4$. On this basis I have plotted the apparently reliable analyses of these minerals on a composition diagram (Fig. 9). On the vertical axis is plotted the percentage of MgO present when it has been determined, this being the most important foreign oxide. As the figure shows, it can reach nearly 10 %. On the whole the analyses are distributed rather evenly from $Fe_3O_4$ to $Mn_3O_4$. There is, however, one marked gap without analyses, between 70—90 % $Mn_3O_4$. Chance alone is insufficient to explain this; and a study of the phase diagram (Fig. 7) reveals the true reason. From the curve bounding the two phase region it can be seen that between 70—85 % $Mn_3O_4$ temperatures of 700° and higher are necessary for the formation of homogeneous phases. The absence of vredenburgites of this composition interval is evidently due to the fact that these temperatures are higher that were prevalent during the formation of this mineral in the manganese ore deposits. Hence the absence of vredenburgites in this interval, and hence the gap in the series of analyses. The vredenburgites hitherto described appear to have been formed at temperatures between 500° and 700°.

Some words of explanation are necessary regarding some of the analyses plotted in Fig. 9. Nos. 3 and 6 are of specimens of magnetite from Väster Silvberg in Dalarna (Sweden) for which Weibull (120) initiated the subspecific name manganmagnetite. This name has been used occasionally in later years for magnetites containing manganese. However, I have preferred not to include manganmagnetite among the names for the different species in the $Fe_3O_4$-$Mn_3O_4$ system, on account of the possibility of confusion with manganomagnetite. Manganomagnetite was described by Flink from Långban and has a very different composition from Weibull's manganmagnetite, containing more manganese than iron and falling within the field of vredenburgite. Manganmagnetite may be an excellent name for specimens of magnetite containing insufficient manganese to be classed as jacobsite, but to prevent confusion it is best that the name be dropped.

This investigation has also resulted in the final writing-off of manganonagnetite as a mineral name. Flink described this mineral in 1885 (24, 5) and realized that it was a spinel with affinities with magnetite and acobsite, but on account of its high content of manganese, much igher than that of any jacobsite analysed up to that time, he decided o make it a new species and called it magnanomagnetite. The name as not won general acceptance, however, and in the mineralogical andbooks manganomagnetite is classed as synonymous with jacobsite.

When, however, the composition of manganomagnetite is plotted n the composition diagram it falls not in the jacobsite field, but in the redenburgite field! (Fig. 9, no. 21). As Flink described manganonagnetite while he was connected with the Mineralogical Institute of his university it was a simple matter to find his original material mong the type collections and reexamine it to confirm that it really vas vredenburgite. Powder photographs were first made of his analysed pecimens, but these showed only the lines of jacobsite, hausmannite ines being completely missing. However, since the composition of nanganomagnetite was so close to the boundary of vredenburgite gainst jacobsite there was always the possibility that the amount of hausmannite in the vredenburgite intergrowth was so small that t would fail to give reflections in the powder photographs. Polished ections were then made of the specimens, and this was found to be the ase. One polished section showed extremely narrow lamellae of hausnannite evenly distributed in the characteristic intergrowth, whereas nother polished section showed no lamellae at all. However, it proved quite impossible to obtain good polished sections of these specimens; hey had such a highly developed octahedral parting that they could e crushed to a powder between the fingers, although the hardness of he mineral itself is about that of magnetite or jacobsite. Thus the surace of the polished sections was interlaced with grooves and triangular its in the directions of this octahedral parting. I have not observed his feature in any other specimen of vredenburgite or jacobsite, and elieve it to be due to submicroscopic lamellae of hausmannite which ave separated along these octahedral planes. In other vredenburgites which contain more manganese the hausmannite lamellae can grow vider and then do not have the same disintegrating effect.[1]

---

[1] In this connection it is interesting to note that Schneiderhöhn and Ramdohr, in their ook on ore-microscopy (93, p. 579) record a specimen of »stark Mn-haltiger Magnetit» rom Tallgruvan, Norberg, Sweden, which showed an extraordinarily well-developed leavage, and suggest that this cleavage may be related to the high manganese content. However, according to an oral communication from Professor P. Geijer, who has decribed the Tallgruvan paragenesis, no especially high manganese percentage is present here. Furthermore, this characteristic cleavage is found in almost all Swedish magnetites hat are associated with borates, and one analysed sample proved to contain only 0.18 % MnO.

Thus Flink recognized at Långban what is now known as vredenburgite over twenty years before Fermor described this mineral from the Indian manganese ores. At the time neither Flink nor Fermor had any idea of the true nature of this mineral as an oriented intergrowth of jacobsite and hausmannite, this being first recognised as late as 1931, when the results obtained by Orcel and Pavlovitch and Schneiderhöhn and Ramdohr from the study of polished sections were published. Thus on priority alone the specific name vredenburgite should be renounced in favour of manganomagnetite. However — fortunately — there are ample grounds for not reviving the old name manganomagnetite. Firstly the name vredenburgite has become established as a result of the numerous investigations on this mineral during the past 15 years; secondly, and perhaps more important, the name manganomagnetite is false in signification, and can be rejected on this ground. Manganomagnetite signifies a manganese-rich magnetite, whereas Flink described what he realized was actually a manganese-rich jacobsite, and it is thus misleading that such a mineral should receive a name suggesting it to be a subspecies of magnetite. Under the circumstances priority is abandoned in this case and vredenburgite retained as the name for those minerals whose composition falls within the area of immiscibility in the $Fe_3O_4$-$Mn_3O_4$ system.

Another analysis about which a few words may be said is that of vredenburgite from Jakobsberg, no. 26 in Fig. 9. This specimen was analysed and described by Johansson in 1928 (49). He had examined polished sections of it and observed that it was not homogeneous, but an intergrowth of two minerals, hausmannite and a spinel. He thus fully understood its true nature, but did not discuss it further, and it remained for Schneiderhöhn and Ramdohr (93, p. 603) to point out that Johansson's material was undoubtedly vredenburgite. During this investigation I examined a number of specimens from Jakobsberg and found several labelled as jacobsite were actually vredenburgite. It is probable that vredenburgite was not at all uncommon at Jakobsberg, but the chances of finding any specimens there now are small, as the mine has been abandoned and there is little to be seen and collected on the old dumps.

During the past fifteen years a considerable literature has grown up around the vredenburgite from India, which has been the only material available to previous investigators. The microscopical features of this mineral and of the ores in which it occurs have been described by Orcel and Pavlovitch, Schneiderhöhn and Ramdohr, and more recently by Dunn (20). Some observations on polished sections have also been made by Deb (16), who in addition made the magnetic measurements referred to in a previous section and also investigated vredenburgite with powder photographs. In this way he could confirm that jacobsite was the main constituent of the intergrowth, but was unable to say anything about the other phase — probably because it (the hausmannite) had been largely replaced by pyrolusite and psilomelane and so failed to give its characteristic reflections in the powder photographs.

In addition to these physical investigations, an extensive investigation of the chemical composition of vredenburgite has been carried out by M. R. Anantanarayana Iyer of the Mysore Geological Department (44, 45). He was interested in finding a suitable formula for this mineral, and for this purpose he made five new analyses (Table 1). He also made a series of experiments with a view to separating the different minerals in vredenburgite by means of their selective solubility in a solution of oxalic and sulphuric acids, and in this way to determine their respective compositions.

**Table 1.**

Analyses of »vredenburgite» by M. R. Anantanarayana Iyer.

| | 1. | 2. | 3. | 4. | 5. |
|---|---|---|---|---|---|
| $MnO_2$ | 15.11 | 25.73 | 26.26 | 49.84 | 52.86 |
| $MnO$ | 33.11 | 30.84 | 32.09 | 11.57 | 12.76 |
| $Fe_2O_3$ | 49.78 | 39.15 | 38.15 | 26.44 | 22.93 |
| | 98.00 | 95.72 | 96.50 | 87.85 | 88.55 |

1. No. 779. Vredenburgite in psilomelane-braunite rock. Beldongri manganese mine, Nagpur district, Central Provinces.
2. No. 690. Devada manganese mines, Vizagapatam district.
3. No. 691. Kodur manganese mine, Vizagapatam district.
4. No. 684 M. Vredenburgite magnetically separated from vesicular psilomelane, Kodur manganese mine.
5. No. 692. Kodur manganese mine.

(The numbers of the specimens are those of the Geological Survey of India's collections.)

An unfortunate deficiency in Iyer's work, and one that largely nullifies his conclusions, is that there was no control over the mineralogical composition of his specimens, either with polished sections or by other means. He apparently relied upon the labelling for the identity of his material with vredenburgite. Actually two of his specimens were not, and never had been vredenburgite. By a curious chance I was able to obtain samples of Iyer's material and investigate them with polished sections and by X-rays. Iyer sent these samples to Professor Ramdohr in Berlin, and Ramdohr, on hearing that we were investigating vredenburgite in this institute, generously loaned them to us for the purpose of this investigation. The results of the examination of Iyer's specimens were as follows:

779. Polished section: not vredenburgite, but homogeneous jacobsite. The jacobsite is intersected by an irregular network of very narrow

veins of a white mineral, evidently pyrolusite or psilomelane; this mineral is later than the jacobsite, replacing it along cracks.

X-ray: powder photographs with sharp lines; all lines those of jacobsite; $a = 8.49$ A.

690. Polished section: shows the typical structure of vredenburgite clearly even in ordinary light, as the hausmannite lamellae are completely replaced by pyrolusite or psilomelane, which is much whiter than the jacobsite. (In fresh vredenburgites, such as that from Långban, in which the hausmannite lamellae are unaltered, these lamellae appear somewhat greyer than the jacobsite, but do not stand out very clearly in ordinary light.)

X-ray: lines in the powder photographs somewhat diffuse, only jacobsite lines visible: $a = 8.44$ A.

691. Polished section: typical vredenburgite structure; the lamellae of two sorts, one wide and of considerable length, the other narrow and short. Lamellae largely replaced by psilomelane or pyrolusite, but isolated and irregular remnants of hausmannite in the middle of the lamellae; replacement has gone farther in the wide lamellae than in the narrow, some of the latter still consisting entirely of hausmannite. The specimen is also veined with rather wide veins of pyrolusite or psilomelane.

X-ray: lines in the powder photographs a little diffuse, but both jacobsite and hausmannite lines present; jacobsite $a = 8.48$ A, hausmannite $a = 8.17$ A, $c = 9.33$ A.

684. Polished section: the specimen consists of a finegrained aggregate of psilomelane with scattered remnants of jacobsite: in one place the jacobsite showed traces of hausmannite lamellae, but otherwise it was completely homogeneous. Apparently the jacobsite once formed the whole specimen, but has been almost completely replaced by manganese-rich oxidizing solutions.

X-ray: a magnetic concentrate was prepared, in order to find out how pure a sample of the jacobsite could be obtained in this manner, but the powder photograph showed strong lines both of jacobsite and psilomelane, indicating that the separation was very incomplete; $a$ for jacobsite 8.42 A.

692. Polished section: vredenburgite present, but as in 690 the hausmannite lamellae are completely replaced by pyrolusite or psilomelane; besides this replacement there is also a considerable amount of these minerals present as isolated aggregates and veins, the vredenburgite itself making up only 50—70 % of the whole specimen.

X-ray: the material for the powder photographs was separated from the pyrolusite or psilomelane by a magnet; the powder photograph showed only jacobsite lines, $a = 8.40$ A.

It is evident that such material is quite unsuited for investigations into the composition of the primary vredenburgite.

Nos. 684 M and 692 are so altered and impure that no good purpose is served by considering them further. Their analyses are not to be reckoned with as vredenburgite, and are not included in the analyses plotted on the composition diagram (Fig. 9).

No. 779 is the least altered of all the specimens but unhappily is not vredenburgite at all, but jacobsite; apart from the polished section, this is shown by the fact that when Iyer's analysis is calculated as $(Mn, Fe)_3O_4$ and plotted on Fig. 9 it falls at 50 % $Mn_3O_4$ (No. 19), within the jacobsite field.[1]

Thus of Iyer's five analyses only two, nos. 690 and 691, can be considered as vredenburgite, and even in these the hausmannite is partly or completely replaced by later alteration to pyrolusite or psilomelane.

Iyer realized that there was free $MnO_2$ in all his specimens, and evidently believed that this $MnO_2$ had been formed quite independently of the vredenburgite, for he considered that if all this free $MnO_2$ could be removed from his specimens, then the residue would be vredenburgite, and an analysis of this residue would thus give the composition of the primary vredenburgite. He therefore treated the powdered specimens with sodium oxalate and dilute sulphuric acid to remove the free $MnO_2$, analysed the residues, and from these analyses derived a formula which he considered to be the formula of vredenburgite itself.

The procedure, however, is fundamentally unsound. The minerals present in Iyer's specimens were jacobsite, pyrolusite, psilomelane, and in 691 hausmannite also. Iyer made no experiments on the relative rates of solution of these minerals in sodium oxalate-dilute sulphuric acid mixtures, so his assumption that the residue after treatment was homogeneous is very shaky. Some qualitative tests which I have made with the above minerals show that jacobsite is the least attacked by such mixtures, so that Iyer's residues were probably largely jacobsite. However, in those specimens in which vredenburgite was actually present — 690, 691, and 692 — it is extremely doubtful whether treatment with sodium oxalate and dilute sulphuric acid, however long continued, would ever leave a residue of pure jacobsite, since the oriented intergrowth which is vredenburgite is so fine-grained that even in the finest powder the grains would not be mono-mineralic, but consist of jacobsite with lamellae of hausmannite, or in these specimens lamellae of pyrolusite and psilomelane, and the residue would thus always contain $MnO_2$ in excess. Even if Iyer's procedure had accomplished what he believed it to do, then the analyses of his residues would by no means correspond to vredenburgite, but only to the jacobsite phase in the vredenburgite.

---

[1] Dunn (20) examined polished sections of specimens marked with the same number, 779, from the Geological Survey of India's collection, and remarks that they represent the purest form of jacobsite so far found in India. He had two analyses made and these analyses (15 and 18 in Fig. 9) lie rather close to that of Iyer. Presumably Dunn's and Iyer's material of 779 were part of the same batch.

I have discussed Iyer's work rather exhaustively, as his results were used by Fermor (23) as a basis for distinguishing between the original vredenburgite and Iyer's 690 and 691, and creating a new name — devadite — for the latter. His grounds for doing this were that Iyer's 690 and 691 from Devada and Kodur contained more iron than the type specimens from Beldongri and Garividi. The extent of this difference is clearly seen by reference to Fig. 9 — the Devada-Kodur pair are nos. 22 and 23, the Beldongri-Garividi pair are nos. 24 and 25. Fermor evidently realized that these minerals formed part of a continuous series, as he suggested that further research might result in the discovery of specimens intermediate in composition and foresaw the possibility of introducing still another name to cover such specimens! He also foresaw that ambiguity would arise through the use of the name vredenburgite in an extended sense for all specimens showing the typical intergrowth and thus including devadite, and in a restricted sense for those specimens identical chemically with the type material from Beldongri and Garividi. His solution for this difficulty was simple; retain the term vredenburgite in the extended sense, and propose a special term for the original material. For the original material he suggested the name garividite; but with commendable restraint he remarks (23, p. 277) »This refinement seems unnecessary, however, at present».

A brief consideration of Fig. 9 and the previous discussion on the $Fe_3O_4$-$Mn_3O_4$ system shows the lack of reason in Fermor's proposals. It is neither necessary nor desirable to divide up the vredenburgite field into two or more groups of minerals. On the contrary the minerals in this field definitely belong together. Names such as devadite and garividite have no place in a systematic terminology, and are stillborn.

All analyses of the Indian vredenburgites show $MnO_2$ in excess of that required for the simple vredenburgite formula $(Mn, Fe)_3O_4$. Iyer and Fermor regard this as evidence that the primary vredenburgite itself contained more oxygen than corresponded to the $R_3O_4$ formula. When Iyer found that the residues obtained after prolonged treatment of his specimens with sodium oxalate and dilute sulphuric acid contained excess $MnO_2$ he concluded that this $MnO_2$ was present in the primary vredenburgite. This result can be otherwise explained. As shown above, it is doubtful if even prolonged treatment with sodium oxalate and dilute sulphuric acid sufficed to remove all the free $MnO_2$ from his specimens. In addition, even if excess $MnO_2$ were present in these specimens, it could be counterbalanced by the presence of lower oxides such as MgO, which were not determined in Iyer's analyses, and the formula would still be $R_3O_4$. Qualitative tests have shown that at least magnesium is present in all Iyer's specimens, and this variation in composition is reflected in the lattice dimensions of the jacobsite in them, which vary from 8.49 A down to 8.40 A, according to the amount of foreign elements present in solid solution in the iron-manganese oxide.

Fermor, in his original description of vredenburgite (21, 22), believed that the excess $MnO_2$ was an integral part of this mineral and gave it the formula $3Mn_3O_4 \cdot 2Fe_2O_3$. In his latest paper (23) he takes up Iyer's results and, combining them with his earlier work, develops this idea still further. He takes the original analyses of vredenburgite and those of Iyer's specimens 690 and 691, assumes that they give the composition of the primary vredenburgite, and in this way gets a formula for this substance with more oxygen than corresponds with the formula $R_3O_4$. He therefore concludes that the primary vredenburgite was not a spinellid, and that on disintegration it broke down not into jacobsite and hausmannite alone, but into jacobsite, hausmannite, and free $MnO_2$, the free $MnO_2$ being present as the minerals pyrolusite (or polianite) and psilomelane.

Fermor supports his hypothesis with the belief that there is no evidence that the pyrolusite or polianite which is observed in polished sections of the Indian vredenburgite is later in age than the undoubtedly primary jacobsite and hausmannite. He completely overlooks the observations of Schneiderhöhn and Ramdohr (93) and Dunn (20) — the latter on Fermor's original specimens! — that the pyrolusite and psilomelane are products of the selective replacement and are therefore secondary. I have examined polished sections of a number of specimens of Indian vredenburgite from different localities and have observed pyrolusite or psilomelane in all of them; in no case was there anything to indicate that these minerals were primary; they typically replace the hausmannite lamellae and leave the jacobsite largely unaffected, indicating the greater resistance of the latter mineral to alteration.

On these grounds Fermor's hypothesis of primary $MnO_2$ in vredenburgite must be rejected. However, I do not wish to deny the possibility of the existence of compounds of the type $R_3O_4$ with oxygen in excess of the stoichiometric formula. In fact such compounds are known — e. g. $\gamma$-$Fe_2O_3$ and $\gamma$-$Mn_2O_3$ — and Verwey and van Bruggen (108) have found that $Fe_2O_3$ is soluble in $Mn_3O_4$ at high temperatures, giving substances with structures like those of the $\gamma$-forms of the sesquioxides, with vacant metal positions in the spinel lattice. My standpoint is, however, that no satisfactory evidence has been advanced, either by Iyer or Fermor, that the $MnO_2$ in specimens of the Indian vredenburgite represents such excess oxygen. If such excess oxygen were present in these specimens, would it not appear as primary bixbyite $(Fe, Mn)_2O_3$, rather than as primary $MnO_2$? At Långban, for example, polished sections show the typical intergrowth of hausmannite and vredenburgite, and also a small amount of bixbyite. Although this bixbyite has apparently been formed at the same time as the vredenburgite it is in no way related to the intergrowth of hausmannite and jacobsite, but occurs as isolated individual crystals. Here, at least, there is nothing to suggest that the excess oxygen represented by the $(Mn, Fe)_2O_3$ was at one time an original constituent of the primary vredenburgite.

### The system $Fe_2O_3 - Mn_2O_3$.

The phase diagram of this system (Fig. 10) was worked out according to the same methods used in the investigation of the system $Fe_3O_4$-$Mn_3O_4$. Preparations with known proportions of iron and manganese were obtained by precipitation with sodium hydroxide from a solution of ferrous and manganous sulphate mixed in the required amounts. The precipitates were washed free from sulphate and dried in air at 165° for 24 hours. They were then heated in air at different temperatures between 600° and 1000°, the period of heating being 48 hours in all cases. It is believed that this period was sufficiently long for the preparations to reach equilibrium under the experimental conditions. The lower temperature, 600°, was chosen to avoid the possible formation of $MnO_2$; the upper temperature, 1000°, was controlled by the dissociation of these sesquioxides at higher temperatures. Pure $Mn_2O_3$ dissociates when heated in air at 940°, and the temperature of dissociation slowly increases with increase in the amount of $Fe_2O_3$ present, until a sample containing 70 % $Fe_2O_3$ begins to dissociate at about 1020°. With increase of $Fe_2O_3$ beyond 70 % the temperature of dissociation increases rapidly, pure $Fe_2O_3$ dissociating at 1388°.

The phases present were determined by X-ray investigation. No intermediate compounds of the two oxides were found. The only phases which occurred were the cubic form of $Mn_2O_3$, which was found to dissolve up to about 60 % $Fe_2O_3$, and the $\alpha$-form of $Fe_2O_3$, with about

10—15 % $Mn_2O_3$ in solid solution. The greatest experimental difficulty in the determination of the phase relations in this system by X-ray methods is that the lattice dimensions of $Mn_2O_3$ do not change perceptibly as the amount of $Fe_2O_3$ in solid solution increases, nor do the lattice dimensions of $Fe_2O_3$ change as the amount of $Mn_2O_3$ in solid solution increases. The cell edge of pure $Mn_2O_3$ was found to be 9.400 A, that of a sample containing 60 % $Fe_2O_3$ in solid solution 9.386 A, not greatly outside the limits of the error of measurement (± 0.005 A in this case). No difference in lattice dimensions could be seen between pure $Fe_2O_3$ and $Fe_2O_3$ containing the maximum amount of $Mn_2O_3$ in solid solution. Therefore it was not possible to fix the limits of solid solution at a certain temperature by determining the lattice dimensions of the two phases in a sample heterogeneous at that temperature, and from the lattice dimensions the composition of the two phases. Instead the only method available was to examine the powder photographs carefully and detect when all the lines present belonged to a single phase, or when lines of both the $Fe_2O_3$ and the $Mn_2O_3$ phase were present. The sensitivity of this method is clearly dependent upon the smallest amount of the one phase which will give a characteristic line when mixed with the other phase. Fortunately, in the $Fe_2O_3$-$Mn_2O_3$ system the sensitivity of this method is greater than usual; by actual experiment it was found that as little as 5 % $Fe_2O_3$ mixed with $Mn_2O_3$ was sufficient to bring out clearly the 321 reflection of $Fe_2O_3$, and as little as 5 % $Mn_2O_3$ in $Fe_2O_3$ was sufficient to develop the 440 reflection of $Mn_2O_3$. Thus if a powder photograph of a certain sample showed the lines of one phase only, then it was certain that the sample in question contained not more than about 2—3 % of the other phase. By this means the phase diagram (Fig. 10) was built up.

I had hoped to get an additional check on the phase boundaries by measurements of the magnetic properties of the different preparations. However, this proved to be impossible, as the susceptibility of all the preparations was smaller than could be measured with the apparatus available.

It is desirable to point out that there is one source of inaccuracy in the determination of the phase boundaries of Fig. 10. It lies in the temperature control during the heating of the preparations at the different temperatures. The nature of the equipment made it impossible to control the temperature of the electric furnaces used with an accuracy of greater than about ± 20°. I do not believe, however, that the possible variation in temperature during the heating of the preparations was sufficient to produce any significant error in the systematic investigation.

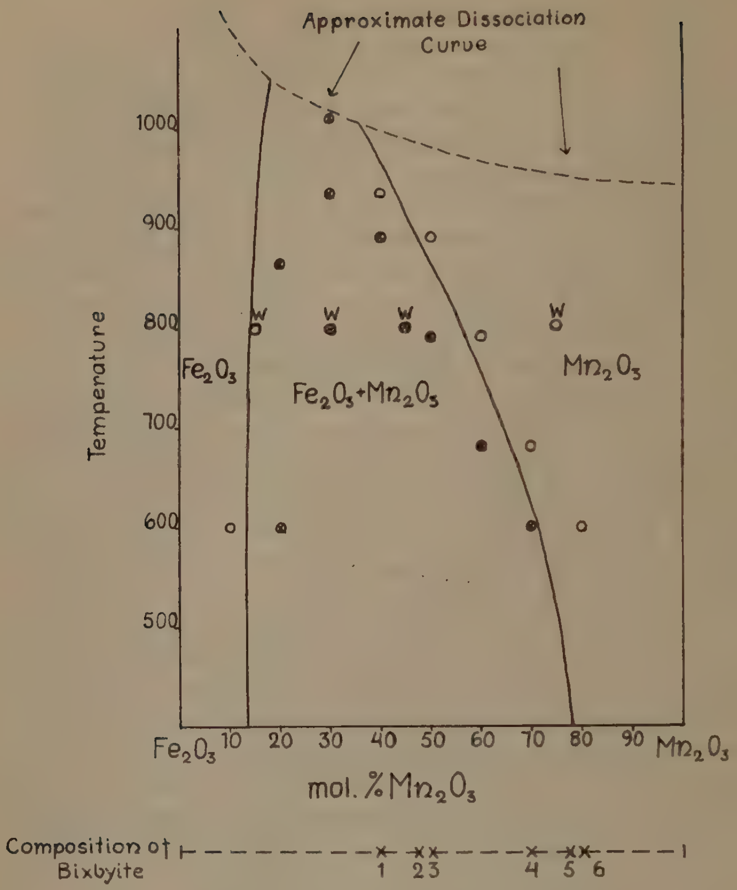


Figure 10. The system $Fe_2O_3$—$Mn_2O_3$.

○ one-phase samples: ⊗ two-phase samples. (The superscript W indicates that the point is taken from Wretblad's investigation.)

Composition of bixbyite, localities: 1 & 2, Rio Chubut, Patagonia; 3, Thomas Range, Utah; 4, Sitapar, India; 5, Långban, Sweden; 6, Postmasburg, South Africa.

Considering now the phase diagram in detail, it is seen that the maximum solubility of $Mn_2O_3$ in $Fe_2O_3$ is about 10—15 %, and does not vary greatly with change of temperature. The maximum solubility of $Fe_2O_3$ in $Mn_2O_3$, on the other hand, is very dependent on the temperature, increasing rapidly from less than 30 % at 600° to nearly 70 % at 1000°. From the shape of the curves it would appear that at ordinary temperatures the maximum solubility of $Mn_2O_3$ in $Fe_2O_3$ is 10 % or a little more, that of $Fe_2O_3$ in $Mn_2O_3$ about 20 %.

Only two investigators, Wretblad (126) and Montoro (67), have previously studied the system $Fe_2O_3$-$Mn_2O_3$, and their results are more in the nature of isolated observations than a systematic study. Wretblad made his preparations, which contained 15 %, 30 %, 45 %, and 75 % $Mn_2O_3$, by heating either iron-manganese alloys or mixed crystals of $MnCl_2$ and $FeCl_2$ in a stream of oxygen at 800°. He investigated the products by means of powder photographs in the same way as in the present investigation. His results are plotted on the phase diagram (Fig. 10), and are in agreement with my own observations. Wretblad observed that the lattice dimensions of $Fe_2O_3$ and $Mn_2O_3$ did not vary with the formation of solid solutions. He also noticed that the occurrence of the Utah bixbyite, with approximately 50 % $Fe_2O_3$ in solid solution in $Mn_2O_3$, stood in apparent contradiction to his results on the limits of mutual solubility of the two oxides.

Montoro also found that the lattice dimensions of $Fe_2O_3$ and $Mn_2O_3$ did not change as solid solutions were formed of the two oxides. He disagreed from Wretblad on the extent of the mutual solubility, stating that the solubility of $Mn_2O_3$ in $Fe_2O_3$ is practically zero, but that $Mn_2O_3$ can take up $Fe_2O_3$ up to a ratio of $Fe_2O_3 : Mn_2O_3$ of 1 : 1. Neither Montoro nor Wretblad seem to have realized that the solubility of two substances in the solid state is dependent on the temperature, generally increasing with rising temperature. Thus the occurrence of a mineral with 50 % $Fe_2O_3$ in solid solution in $Mn_2O_3$ is only apparently inconsistent with Wretblad's result that the solubility of $Fe_2O_3$ in $Mn_2O_3$ is not more than about 40 %. Wretblad's determination is correct for the temperature at which it was made, but only at that temperature. Montoro's statement that the solubility of $Mn_2O_3$ in $Fe_2O_3$ is practically zero is contradictory to the results of both Wretblad and myself; I believe Montoro's statement to be incorrect, but as he gives no indication in his publication as to how he came to that result it is not possible to criticize it.

The discussion of the mineralogical aspects of the system $Fe_2O_3$-$Mn_2O_3$ is handicapped by the comparative rarity of bixbyite, with consequent lack of data concerning its variation in composition and its paragenesis. However, on Fig. 10 I have plotted the chemical composition of the recorded bixbyites, expressed as $(Mn, Fe)_2O_3$ without consideration of the presence of foreign elements in solid solution. Nos. 1 and 2 are bixbyites from Rio Chubut, Patagonia, analysed by Corti (15) and de Muozo (17); 3 is the original bixbyite from Thomas Range, Utah, described by Penfield and Foote (79); 4 is bixbyite (originally sitaparite) from Sitapar in India (21); 5 is bixbyite from Långban which I described in 1942 (57); and 6 is bixbyite from the manganese ores of

Postmasburg in South Africa.[1] The bixbyites fall into two groups: those with between 50—60 % $Fe_2O_3$, and those with up to 30 % $Fe_2O_3$. From the phase diagram it can be seen that temperatures of 850°—950° are necessary for the formation of homogeneous mix-crystals of $Mn_2O_3$ with 50—60 % $Fe_2O_3$. The formation of mix-crystals of $Mn_2O_3$ with amounts of $Fe_2O_3$ up to 30 %, however, does not require nearly such high temperatures, up to 650° being sufficient. An attempt to read off the temperature of formation of the natural bixbyites from this consideration of the phase diagram is somewhat venturesome, as the small amounts of other elements present in solid solution, especially titanium, may have a considerable effect on the solubility of $Fe_2O_3$ in $Mn_2O_3$. However, it can safely be said that bixbyites 1, 2, and 3 have been formed at considerably higher temperatures than bixbyites 4, 5, and 6. The essential correctness of the above arguments is confirmed by the parageneses of these different bixbyites. Bixbyites 1, 2, and 3 occur in immediate connection with acidic extrusives, bixbyites 4, 5, and 6 in metamorphosed manganese ores. The bixbyite from Utah occurs in rhyolite, associated with topaz, garnet, beryl, hematite, and quartz; according to Montgomery (65) the bixbyite crystals are generally found as clusters on and partly included in crystals of topaz, the two minerals having crystallized practically at the same time. None of those who have written about the Patagonian bixbyite appear to have seen the occurrence in the field, but according to their descriptions it occurs in a quartz vein in trachyte, with hematite, ilmenite, biotite, and felspar. Each occurrence is clearly pneumatolytic, and a temperature of formation of 850°—950° is not unreasonably high. The association with hematite both in Utah and Patagonia suggests that the bixbyite crystallized from a medium sufficiently rich in $Fe_2O_3$ to give a bixbyite with the maximum amount of $Fe_2O_3$ in solid solution at the temperature of formation. The parageneses of the bixbyite from Långban, Sitapar, and Postmasburg clearly have no connection with pneumatolytic action. At these localities the bixbyite has been formed as a result of metamorphic processes involving recrystallization of what were probably originally sedimentary manganese ores. It is interesting to note that Schneiderhöhn (94) gives evidence indicating that the formation of bixbyite at Postmasburg has been accompanied by the partial or complete disappearance of hematite, suggesting that the bixbyite has incorporated this $Fe_2O_3$ in its space lattice. I have examined polished sections of bixbyite and its accompanying minerals from Långban, Sitapar, and Postmasburg; although the mineral association is quite different at the three localities, the structural features are similar in indicating metamorphism involving recrystallization, the bixbyite being porphyroblastic in its relations to the other minerals. The degree of recrystallization is much greater in the Långban and Sitapar occurrences than at Postmasburg, indicating a greater intensity of the metamorphic processes, either temperature, or pressure, or both together. Parallel with this the Postmasburg bixbyite appears to contain the least amount of $Fe_2O_3$, although it was formed in an association containing hematite. The inference is that the temperature of metamorphism at Postmasburg was comparatively low, at least about 500° or less.

---

[1] The bixbyite from Postmasburg has never been analysed. It occurs as a component in a compact fine-grained manganese ore, and in all specimens which I have examined it would be extremely difficult to extract sufficient pure bixbyite for a quantitative chemical analysis. However, in a cavity in the compact ore I noticed a number of small (up to 1 mm edge) cubes of this mineral; three or four of these cubes were carefully extracted and heated at 1 120° for several days, being thus converted to $(Mn, Fe)_3O_4$. Powder photographs were made of this product and the lattice dimensions ($a = 8 \cdot 24$ A, $c = 9 \cdot 12$ A) determined in the usual way. The approximate composition could then be read off the graph (Fig. 5) giving the variation of lattice dimensions with composition in the system $Fe_3O_4$-$Mn_3O_4$. In this way it was found that the ratio Mn : Fe was about 80 : 20. No great accuracy is claimed for the method, but it shows that the ratio $Mn_2O_3$ : : $Fe_2O_3$ in the Postmasburg bixbyite is approximately 80 : 20.

The above discussion may seem to read more out of the composition of the known bixbyites and the phase diagram established by laboratory studies than is advisable. I am aware that until further finds of bixbyite have been made in the different parageneses in which it can occur caution is necessary, and the correlation of laboratory studies and mineral analyses must not be pushed too far. However, I look forward to new finds of bixbyite, which will enable such correlation to be placed on a sounder footing. Recently bixbyite was found in some ice-borne blocks of manganese ore at Murjek, in Swedish Lapland, and it will be of great interest to see how the composition of this bixbyite is related to that of previously described bixbyites.

Reference to the phase diagram reveals that the bixbyites from Utah and Patagonia, which have been formed at high temperatures, contain so much $Fe_2O_3$ that they should be metastable at ordinary temperatures, tending to disintegrate into an oriented intergrowth of hematite and a bixbyite containing much less $Fe_2O_3$ in solid solution, similar to vredenburgite in the $Fe_3O_4$-$Mn_3O_4$ system. I have not examined any bixbyite from Patagonia, but specimens from the Utah locality which I have investigated both in polished section and by powder photographs are still completely homogeneous. The conditions of cooling were evidently unfavourable for the crystallization of hematite from the solid solution, and at ordinary temperatures the rate of disintegration is zero..

Turning now to the $Fe_2O_3$ side of the phase diagram, little comment is possible. I have not found any published analysis of hematite which shows more than 1 % $Mn_2O_3$, although the phase diagram indicates that mix-crystals containing up to at least 10 % $Mn_2O_3$ are possible. This can depend on one or several factors: the non-determination of manganese in most analyses, the lack of analyses of hematites from manganiferous deposits, the general isolation of iron and manganese deposits from each other. The most interesting hematites in this connection would be those associated with the iron-rich bixbyites of Utah and Patagonia; there, if anywhere, the conditions favour the formation of hematites with the maximum amount of $Mn_2O_3$ in solid solution. The possibility of investigating this, however, has not been available, owing to the lack of the necessary material.

## Summary and conclusions.

A study has been made of the system $FeO$-$Fe_2O_3$-$MnO$-$Mn_2O_3$ by chemical, physical, and mineralogical investigations, for the purpose of determining the phase relations and in this way to define the limits of the different mineral species and to elucidate their mutual relations. The essential results of this study combined with data from the investigations of others are expressed in Fig. 11. The solid lines show the probable miscibility at ordinary temperatures, the broken lines the limiting miscibility at high temperatures.

In the system $FeO$-$Fe_2O_3$ four phases are found. Wüstite, the compound which has long been known as ferrous oxide, but which always contains more oxygen than corresponds to the formula FeO; it is unstable below 575°, tending to disintegrate into iron and $Fe_3O_4$, and it has not yet been identified as a mineral, the evidence for iozite being a naturally occurring wüstite being negligible. Ferrosic oxide, $Fe_3O_4$, occurring as the mineral magnetite. Ferric oxide, $Fe_2O_3$, which has two polymorphic forms: $\alpha$-$Fe_2O_3$, which occurs as the mineral hematite, $\gamma$-$Fe_2O_3$, which occurs as the mineral maghemite; $\gamma$-$Fe_2O_3$ is a monotropic form, being unstable at all temperatures and tending to invert to $\alpha$-$Fe_2O_3$. The maximum variation in composition of the wüstite phase is from about 75.5 to 77.0 % Fe. $Fe_3O_4$ is miscible with 5 % or less FeO at ordinary temperatures and only a little more at high temperatures; it is miscible with about 7 % $Fe_2O_3$ at ordinary temperatures, but the miscibility increases rather rapidly above 1100°, reaching about 30 % at 1450°. The miscibility of $Fe_3O_4$ in $\alpha$-$Fe_2O_3$ is extremely small at ordinary temperatures, and does not increase greatly until very high temperatures are reached. There is a continuous transition from $Fe_3O_4$ to $\gamma$-$Fe_2O_3$.

In the system $MnO$-$Mn_2O_3$ there are four, or possibly five phases: manganous oxide, MnO, occurring in nature as the mineral manganosite;

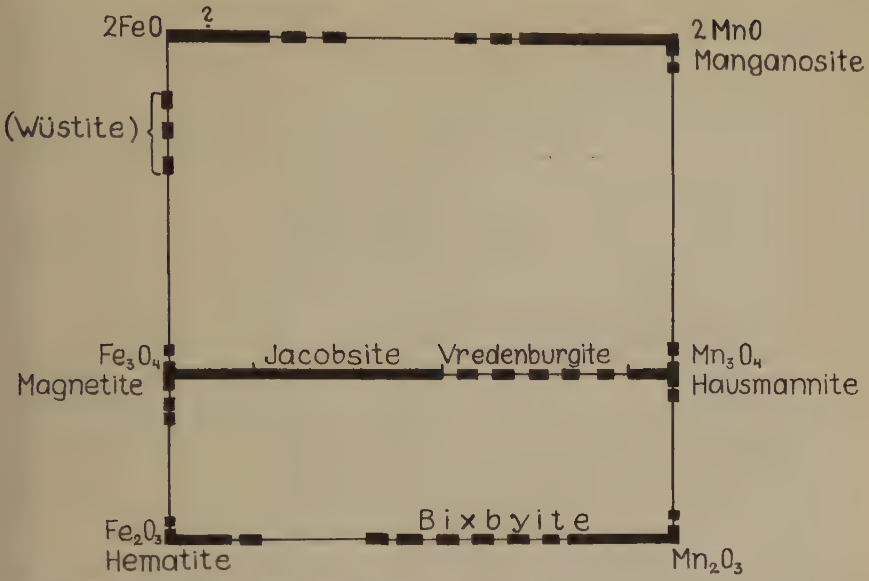


Figure 11. The system $FeO-Fe_2O_3-MnO-Mn_2O_3$. Thick solid lines indicate miscibility at ordinary temperatures; broken lines limiting miscibility at high temperatures.

manganosic oxide, $Mn_3O_4$, occurring as the mineral hausmannite; and manganic oxide, $Mn_2O_3$, which has two, or possibly three polymorphic forms — the stable form, $\alpha$-$Mn_2O_3$, which with some $Fe_2O_3$ in solid solution occurs as the mineral bixbyite, and two monotropic forms, the tetragonal $\gamma$-$Mn_2O_3$ corresponding to $\gamma$-$Fe_2O_3$, and another tetragonal modification perhaps distinct from the $\gamma$-form; the two monotropic forms are not known as minerals. The mutual miscibility of the three stable phases in this system is not certainly known, but is in any case small.

The system FeO-MnO is unimportant mineralogically, as only MnO occurs as a mineral, and is very rare as such. On the other hand this system has considerable significance in the study of slags and of smelting processes. Just what the conditions are at the FeO end of the system is obscure, as pure FeO is unknown, hence the query in Fig. 11. However, it appears that there is an area of immiscibility between the two oxides even at high temperatures and that this area widens somewhat with falling temperature.

$Fe_3O_4$ and $Mn_2O_4$ are completely miscible at high temperatures, in spite of the difference in symmetry between them. The cubic lattice of $Fe_3O_4$ changes to a tetragonal lattice at about 60 % $Mn_3O_4$. At ordinary temperatures there is an area of immiscibility between 54 % and 91 %

$Mn_3O_4$. On the basis of the phase rule diagram the system is divided up into four mineral species: magnetite, from 0—16.7 % $Mn_3O_4$; jacobsite, from 16.7—54 % $Mn_3O_4$; vredenburgite, from 54—91 % $Mn_3O_4$; and hausmannite, from 91—100 % $Mn_3O_4$. The name manganomagnetite is synonymous with vredenburgite, and is therefore discarded; the names devadite and garividite are superfluous. The term manganmagnetite has been used for manganese-bearing magnetites in which the amount of manganese present is less than that required for jacobsite, but the use of this term is to be avoided, on account of the possibility of confusion with manganomagnetite.

In the system $Fe_2O_3$-$Mn_2O_3$ (or rather the system $\alpha$-$Fe_2O_3$—$\alpha$-$Mn_2O_3$, the monotropic forms not being taken into account) the limiting miscibility of $Mn_2O_3$ in $Fe_2O_3$ is about 10—15 % at ordinary temperatures and increases but little with increasing temperature; the miscibility of $Fe_2O_3$ in $Mn_2O_3$ is about 20 % at ordinary temperatures, and increases rapidly above 500°, reaching 60 % at about 950°. This feature is reflected in the composition of bixbyite, which when formed by igneous exhalations at high temperatures contains much more iron than when formed at lower temperatures during the metamorphism of manganese-iron ores. Sitaparite is synonymous with bixbyite, and is therefore discarded.

Thus the mineral species in the system FeO-$Fe_2O_3$-MnO-$Mn_2O_3$ are the following: magnetite, $Fe_3O_4$; hematite, $\alpha$-$Fe_2O_3$; maghemite, $\gamma$-$Fe_2O_3$; manganosite, MnO; hausmannite, $Mn_3O_4$; bixbyite, $\alpha$-$Mn_2O_3$, with up to about 60 % $Fe_2O_3$ in solid solution; jacobsite, $(Fe, Mn)_3O_4$ ($Mn_3O_4$ = 16.7—54 %); and vredenburgite, $(Mn, Fe)_3O_4$ ($Mn_3O_4$ = 54—91 %). The terms iozite, devadite, garividite, and sitaparite are to be removed from the list of valid mineral names.

Mineralogical Institute, University of Stockholm, February 1943.

## List of references.

References not seen by the writer are marked with an asterisk.

1. Aminoff, G. Über die Kristallstruktur von Hausmannit ($MnMn_2O_4$). Z. Krist., 64, 475—490, 1926.
2. Aminoff, G. Lattice Dimensions and Space-group of Braunite. Kgl. Svenska Vetenskapsakad. Handl., 9, No. 5, 14—22, 1931.
3. Andrew, J. H., Maddocks, W. R., & Howat, D. The Equilibrium of Certain Non-Metallic Systems. J. Iron Steel Inst. (London), 124, 283—308, 1931.
4. Baudisch, O. Zur Erkenntnis der Beziehung zwischen Raumstruktur und biokatalytischen Eigenschaften allotroper Eisenoxyde, IV. Ber., 70, 218—223, 1937.
5. Benedicks, C., & Löfquist, H. Über das System Eisen-Sauerstoff. Z. Ver. deut. Ing., 71, 1576—1577, 1927.
6. Benedicks, C., & Löfquist, H. Non-Metallic Inclusions in Iron and Steel. London 1930.
7. Berzelius, J. Untersuchung der Zusammensetzung der eisenhaltigen blausauren Salze. Schweigger's J. Chem. Phys., 30, 1—67, 1820.

8. Blomstrand, C. W. Manganosit, ett nytt mineral från Vermland. Geol. Fören. Förh., 2, 179—183, 1874—75.
9. Broch, E. Präzisionsbestimmung der Gitterkonstanten der Verbindungen MgO, MgS, MgSe, MnO und MnSe. Z. physik. Chem., 127, 446—454, 1927.
10. Brun, A. Quelques recherches sur le volcanisme (neuvième partie, supplement). L'évolution des oxydes du fer. Arch. Sci. phys. nat. (Genève), 5me période, 6, 244—263, 1924. More summarily in Compt. rend. soc. phys. hist. nat. Genève, 41, 94—96, 1924; Schweiz. mineralog. petrog. Mitt., 4, 355—356, 1924; Bull. soc. franç. minéral., 48, 85—89, 1925.
11. Byström, A., & Mason, B. The Crystal Structure of Braunite, $3Mn_2O_3 \cdot MnSiO_3$. Arkiv Kemi, Mineral. Geol., 16B, No. 15, 1943.
12. Caglioti, V., & D'Agostino, O. Ricerche sugli areogeli. I. La struttura di ossidi metallici. Gazz. chim. ital., 66, 543—548, 1936.
13. Chaudron, G., & Forestier, H. Étude de la décomposition du protoxyde de fer. Anomalies de dilatation corrélatives de son instabilité. Compt. rend., 178, 2173—2176, 1924.
14. Chaudron, G., & Forestier, H. Caractères ferromagnétiques du sesquioxyde de fer stable. Compt. rend., 183, 787—789, 1926.
15. Corti, H. Datos sobre una nueva variedad de Bixbyita hallada en el Chubut. Anales asoc. quim. argentina, 19, 109—116, 1931.
16. Deb, S. Données nouvelles sur les propriétés physiques des constituants minéralogiques de la vredenburgite des Indes. Compt. rend., 209, 518—520, 1939.
17. de Muozo, S. C. La Existencia de la Bixbyita en la Patagonia. Neues Jahrb. Mineral. Geol., I, 133—135, 1931.
18. Dubois, P. Hydrate et variétés allotropiques du sesquioxyde de manganèse. Compt. rend., 199, 1416—1418, 1934.
19. Dubois, P. Contribution à l'étude des oxydes du manganèse. Ann. chim., (11) 5, 411—482, 1936.
20. Dunn, J. A. A study of some microscopical aspects of Indian manganese-ores. Trans. Nat. Inst. Sci. India, 1, 103—124, 1936.
21. Fermor, L. L. Three new Manganese-bearing minerals: Vredenburgite, Sitaparite and Juddite. Records Geol. Survey India, 37, 199—212, 1908.
22. Fermor, L. L. The Manganese-Ore Deposits of India. Mem. Geol. Survey India, 37, 1909.
23. Fermor, L. L. Notes on vredenburgite (with devadite) and on sitaparite. Proc. Nat. Inst. Sci. India, 4, 253—286, 1938.
24. Flink, G. Mineralogiska notiser. Nyt Mag. for Naturvidenskaberne, 29, 300–305, 1885.
25. Flink, G. Mineralogiska notiser. I, 1—16 (No. 5). Bihang till Kgl. Svenska Vetenskapsakad. Handl., 12, part II, no. 2, 1—71, 1886.
26. Frebold, G., & Hesemann, J. Über magnetischen und nichtmagnetischen Eisenglanz und seine Bedeutung für die Erzlagerstättenkunde. Centr. Mineral. Geol., A, 314—321, 1926.
27. Fricke, R., & Zerrweck, W. Über Struktur und Wärmeinhalt verschieden dargestellter $\gamma$-Eisen (III)-Oxyde, sowie über die Bildungswärme des Lepidokrokit ($\gamma$-FeOOH). Z. Elektrochem., 43, 52—65, 1937.
28. Frondel, C. Exsolution growths of zincite in manganosite and of manganosite in periclase. Am. Mineral., 25, 534—538, 1940.
29. Gorgeu, A. Sur les oxydes de manganèse naturels. Bull. soc. franç. minéral., 16, 133—148, 1893.
30. Gorgeu, A. Sur les Hausmannites de Suède. Bull. soc. chim., (3) 29, 1109—1111, 1903.
31. Gorgeu, A. Sur une série de spinelles quadratiques artificiels du type hausmannite. Bull. soc. chim., (3) 29, 1111—1117, 1903.
32. Greig, J. W., Posnjak, E., Merwin, H. E., & Sosman, R. B. Equilibrium Relationships of $Fe_3O_4$, $Fe_2O_3$, and Oxygen. Am. J. Sci., (5) 30, 239—316, 1935.
*33. Grieve, J., & White, J. The systems $MnO$-$TiO_2$ and $MnO$-$FeO$-$TiO_2$. J. Roy. Tech. Coll. (Glasgow), 4, 660—670, 1940.
34. Gruner, J. W. Magnetite-Martite-Hematite. Econ. Geol., 21, 375—393, 1926.
35. Hägg, G. Die Kristallstruktur des magnetischen Ferrioxydes, $\gamma$-$Fe_2O_3$. Z. physik. Chem., B29, 95—103, 1935.
36. Haul, R., & Schoon, T. Zur Struktur des ferromagnetischen Eisen (III)-Oxydes $\gamma$-$Fe_2O_3$. Z. physik. Chem., B44, 216—226, 1939.
37. Hay, R., Howat, D. D., & White, J. Slag Systems. J. West Scot. Iron Steel Inst., 41, 97—105, 1934.

38. Heisenberg, W. Zur Theorie des Ferromagnetismus. Z. Physik, 49, 619—636, 1928.
39. Herty, C. H. Fundamental and applied research on the physical chemistry of steel making. U. S. Bur. Mines, Rept. Investigations 3054, 1930.
40. Hewett, D. F., & Schaller, W. T. Braunite from Mason County, Texas. Am. Mineral., 22, 785—789, 1937.
41. Hilpert, S. Genetische und konstitutive Zusammenhänge in den magnetischen Eigenschaften bei Ferriten und Eisenoxyden. Ber., 42, 2248—2261, 1909.
42. Hilpert, S., & Wille, A. Zusammenhänge zwischen Ferromagnetismus und Aufbau der Ferrite. Z. physik. Chem., B18, 291—315, 1932.
43. Iimori, T. A Study of Oxide Films Formed on Heated Iron. Sci. Papers Inst. Phys. Chem. Research (Tokyo), 34, 60—67, 1937—38.
44. Iyer, M. R. A. The Formula proposed for the mineral Vredenburgite. Records Mysore Geol. Dept., 34, 75—84, 1935.
45. Iyer, M. R. A. A Graphical Representation of the Composition of some Manganese minerals including a discussion of the nature of the mineral Vredenburgite. Records Mysore Geol. Dept., 35, 73—85, 1936.
46. Jette, E. R., & Foote, F. An X-Ray Study of the Wüstite (FeO) Solid Solutions. J. Chem. Phys., 1, 29—36, 1933.
47. Jette, E. R., & Foote, F. A Study of the Homogeneity Limits of Wüstite (FeO) by X-ray Methods. Am. Inst. Mining Metal. Engrs., Contrib. No. 7, 9 pp., 1933.
48. Ježek, B. Über Braunit von Minas Geraes. Bull. intern. Acad. Sci. Bohême, 13. 15—20, 1908.
49. Johansson, K. Mineralogische Mitteilungen. Z. Krist., 68, 87—118, 1928.
50. Kordes, E. Kristallchemische Untersuchungen über Aluminiumverbindungen mit spinellartigem Gitterbau und über $\gamma$-$Fe_2O_3$. Z. Krist., 91, 193—228, 1935.
51. Kosmann, Über magnetische Eisenhydroxyde. Z. deut. geol. Ges., 45, 508—509, 1893.
52. Le Blanc, M., & Wehner, G. Beitrag zur Kenntnis der Manganoxyde. Z. physik. Chem., A168, 59—78, 1933.
53. Levi, G. R. Il reticolo cristallino dell'ossido manganoso. Gazz. chim. ital.. 54, 704—708, 1924.
54. Liversidge, A. On Iron Rust Possessing Magnetic Properties. Rep. Australasian Assoc. Advancement Sci., 302—320, 1892.
55. Magnusson, N. H. Långbans Malmtrakt. Sveriges Geol. Undersökning, Ser. Ca, No. 23, 1930.
56. Malaguti, F. Sur le sesquioxyde de fer attirable à l'aimant. Compt. rend., 55, 350—352, 1862; Ann. chim. phys., (3) 69, 214—224, 1863.
57. Mason, B. Bixbyite from Långban. The identity of bixbyite and sitaparite. Geol. Fören. Förh., 64, 117—125, 1942.
58. Mathewson, C. H., Spire, E., & Milligan, W. E. Evolution of the iron-oxygen constitutional diagram. Trans. Am. Soc. Steel Treating, 19, 66—89, 1931.
59. Meneghini, Mineralogical Notices. Am. J. Sci., (2) 14, 60—65, 1852.
60. Merrill, G. P. A Newly Found Meteorite from Admire, Lyon County, Kansas. Proc. U. S. Nat. Museum, 24, 907—913, 1902.
61. Michel, A. Propriétés magnétiques de quelques solutions solides. Ann. chim., (11) 8, 317—423, 1937.
62. Miley, H. A. The thickness of oxide films on iron. Iron Steel Inst. (London), Carnegie Schol. Mem., 25, 197—212, 1936.
63. Miser, H. D., & Fairchild, J. G. Hausmannite in the Batesville district, Arkansas. J. Wash. Acad. Sci., 10, 1—8, 1920.
64. Mixter, W. G. The Heat of Formation and Polymerization of some Oxides and Determination of the Heat of Combination of Water by Fusion with Sodium Peroxide. Am. J. Sci., (4), 23—32, 1915.
65. Montgomery, A. A recent find of bixbyite and associated minerals in the Thomas Range, Utah. Am. Mineral., 19, 82—87, 1934.
66. Montoro, V. Miscibilità fra gli ossidi salini di ferro e di manganese. Gazz. chim ital., 68, 728—733, 1938.
67. Montoro, V. Miscibilità fra i sesquiossidi di ferro e di manganese. Gazz. chim. ital., 70, 145—149, 1940.
68. Newhouse, W. H. The Identity and Genesis of Lodestone Magnetite. Econ. Geol., 24, 62—67, 1929.
69. Newhouse, W. H. Opaque oxides and sulphides in common igneous rocks. Bull. Geol. Soc. Am., 47, 1—52, 1936.

70. Newhouse, W. H., & Glass, J. P. Some Physical Properties of Certain Iron Oxides. Econ. Geol., 31, 699—711, 1936.
71. Nieland, H. Beitrag zur Kenntnis der Deckenbasalte von Westgrönland. Chem. Erde, 6, 591—612, 1931.
72. Ödman, O. H. Mineragraphic Study on the Opaque Minerals in the Lavas from Mt. Elgon, British East Africa. Geol. Fören. Förh., 54, 285—304, 1932.
73. Öhman, E. Röntgenographische Untersuchungen über das System Eisen-Mangan. Z. physik. Chem., B8, 81—110, 1930.
74. Orcel, J., & Pavlovitch, S. Les caractères microscopiques des oxydes de manganèse et des manganites naturels. Bull. soc. franç. minéral., 54, 108—179, 1931.
75. Palache, C. The minerals of Franklin and Sterling Hill, Sussex County, New Jersey. U. S. Geol. Survey, Professional Paper 180, 1935.
76. Palmunen, M. K. On the Ilmenite-Magnetite-Olivinite of Susimäki. Fennia, 45, No. 9, 1—27, 1925.
77. Pauling, L., & Shappell, M. D. The Crystal Structure of Bixbyite and the C-Modification of the Sesquioxides. Z. Krist., 75, 128—142, 1930.
78. Pavlovitch, S. Action de la chaleur sur quelques oxydes de manganèse naturels. Compt. rend., 200, 71—73, 1935.
79. Penfield, S. L., & Foote, H. W. On Bixbyite, a new Mineral, and Notes on the Associated Topaz. Am. J. Sci., (4) 4, 105—108, 1897.
80. Persson, E. Röntgenanalyse der Kupfer-Manganlegierungen. Z. physik. Chem., B9, 25—42, 1930.
81. Pfeil, L. B. The constitution of scale. J. Iron Steel Inst. (London), 123, 237—258, 1931.
82. Plücker, J. Über Intensitätsbestimmung der magnetischen und diamagnetischen Kräfte. Pogg. Ann., 74, 321—379, 1848.
83. Ramdohr, P. Beobachtungen an Magnetit, Ilmenit, Eisenglanz und Überlegungen über das System FeO, $Fe_2O_3$, $TiO_2$. Neues Jahrb. Mineral. Geol., Beilage Band, A54, 320—379, 1926.
84. Rinne, F. Magneteisenerz bei Paracale auf Luzon. Z. prakt. Geol., 10, 115—117, 1902.
85. Robbins, J. Magnetic Peroxide of Iron. Chem. News, 1, 11—12, 1859.
86. Roth, W. A., & Wienert, F. Beiträge zur Thermochemie des Eisens. Arch. Eisenhüttenw., 7, 455—460, 1933—34.
87. Ruhemann, B. Temperaturabhängigkeit der Gitterkonstanten von Manganoxyd. Physik. Z. Sowjetunion, 7, 590—607, 1935.
88. Sachse, H., & Haase, R. Die magnetischen Umwandlungen des regulären Ferrioxyds. Z. physik. Chem., A148, 401—412, 1930.
89. Schenck, R., & Dingmann, T. Gleichgewichtsuntersuchungen über die Reduktions-, Oxydations- und Kohlungsvorgänge beim Eisen. III. Z. anorg. allgem. Chem., 166, 113—154, 1927.
90. Schenck, H., & Hengler, E. Untersuchungen über das System Eisen-Sauerstoff. Arch. Eisenhüttenw., 5, 209—214, 1931—32.
91. Schlaepfer, M., & Niggli, P. Neue Beiträge zur hydrothermalen Silikatbildung. Z. anorg. Chem., 87, 52—80, 1914.
92. Schmahl, N. G. Die Beziehungen zwischen Sauerstoffdruck, Temperatur und Zusammensetzung im System $Fe_2O_3$-$Fe_3O_4$. Z. Elektrochem., 47, 821—835, 1941.
93. Schneiderhöhn, H., & Ramdohr, P. Lehrbuch der Erzmikroskopie, Band 2, Berlin 1931.
94. Schneiderhöhn, H. Mineralbestand und Gefüge der Manganerze von Postmasburg, Griqualand-West, Südafrika. Neues Jahrb. Mineral. Geol., Beilage Band, 64, 701—726, 1932.
95. Shannon, E. V. The oxidation of meteoric irons with comparative descriptions of two new examples of magnetic iron oxides from terrestrial sources. Proc. U. S. Nat. Museum, 72, art. 21, 15pp., 1927.
96. Shepherd, E. S. The Gases in Rocks and Some Related Problems. Am. J. Sci., (5) 35 A, 311—351, 1938.
97. Simon, A., & Fehér, F. Beiträge zur Kenntnis von Oxyden. VI. Mitt. Zur Kenntnis der Oxyde des Mangans. Z. Elektrochem., 38, 137—148, 1932.
98. Sosman, R. B., & Hostetter, J. C. The Oxides of Iron. I. Solid Solution in the System $Fe_2O_3$-$Fe_3O_4$. J. Am. Chem. Soc., 38, 807—833, 1916.
99. Sosman, R. B., & Hostetter, J. C. The Ferrous Iron Content and Magnetic Susceptibility of Some Artificial and Natural Oxides of Iron; Zonal Growth in Hematite, and Its Bearing on the Origin of Certain Iron Ores. Bull. Am. Inst. Mining Engrs., 126, 907—931, 933—943, 1917.

100. Sosman, R. B. Some problems of the oxides of iron. J. Wash. Acad. Sci., 7, 55—72, 1917.
101. Sosman, R. B., & Posnjak, E. Ferromagnetic ferric oxide, artificial and natural. J. Wash. Acad. Sci., 15, 329—342, 1925.
102. Strock, L. W. A Classification of Crystal Structures with Defect Lattices. Z. Krist. 93, 285—311, 1936.
103. Thewlis, J. The Structure of Ferromagnetic Ferric Oxide. Phil. Mag., (7) 12, 1089—1106, 1931.
104. Tigerschiöld, M. Järnets oxider från termodynamisk synpunkt. Jernkontorets Annaler, 67—105, 1923.
105. Twenhofel, L. H. Changes in the Oxidation of Iron in Magnetite. Econ. Geol., 22, 180—188, 1927.
106. van Arkel, A. E., Verwey, E. J. W., & van Bruggen, M. G. Ferrites I. Rec. trav. chim., 55, 331—339, 1936.
107. Verwey, E. J. W. The Crystal Structure of $\gamma$-$Fe_2O_3$ and $\gamma$-$Al_2O_3$. Z. Krist., 91, 65—69, 1935.
108. Verwey, E. J. W., & van Bruggen, M. G. Structure of solid Solutions of $Fe_2O_3$ in $Mn_3O_4$. Z. Krist., 92, 136—138, 1935.
109. Verwey, E. J. W., & de Boer, J. H. Cation arrangement in a few oxides with crystal structures of the spinel type. Rec. trav. chim., 55, 531—540, 1936.
110. Vogel, R., & Martin, E. Das System Eisenoxydul-Eisenoxyduloxyd. Arch. Eisenhüttenw., 6, 109—111, 1932—33.
111. Voit, F. W. Die Eisenerzlateritlägerstätte des Donderbary und die Möglichkeit einer Hochofen- bzw. Eisenindustrie in Surinam (Niederländisch-Guyana). Z. prakt. Geol., 30, 17—24, 1922.
112. von Kobell, F. Grundzüge der Mineralogie, p. 304. Nürnberg, 1838.
113. Wagner, P. A. Changes in the Oxidation of Iron in Magnetite. Econ. Geol., 22, 845—846, 1927.
114. Wagner, P. A. The Iron deposits of the Union of South Africa. Mem. Geol. Survey South Africa, 26, pp. 18, 29, 1928.
115. Walker, T. L. Lodestone from Bon Accord, Transvaal. Univ. Toronto Studies, Geol. Ser., 29, 17—19, 1930.
116. Walker, T. L. Polarity in Magnetite. Univ. Toronto Studies, Geol. Ser., 30, 15—19, 1931.
117. Wartenberg, H. v., & Gurr, W. Schmelzdiagramme höchstfeuerfester Oxyde. III. Z. anorg. allgem. Chem., 196, 374—383, 1931.
118. Wartenberg, H. v., & Reusch, H. J. Schmelzdiagramme höchstfeuerfester Oxyde. VI. Berichtigung. Z. anorg. allgem. Chem., 208, 380—381, 1932.
119. Wedekind, E., & Horst, C. Die Magnetisierbarkeit der Oxyde des Mangans, Chroms, Urans, Molybdäns und Wolframs. Ber., 48, 105—112, 1915.
120. Weibull, M. Untersuchung schwedischer Minerale. Mineralog. petrog. Mitt., 7, 108—121, 1886.
121. Welo, L. A., & Baudisch, O. The Two-Stage Transformation of Magnetite into Hematite. Phil. Mag., (6) 50, 399—408, 1925.
122. Welo, L. A., & Baudisch, O. Ferromagnetism in the Oxide obtained by Dehydration of Gamma Ferric Oxide Hydrate. Phil. Mag., (7) 17, 753—768, 1934.
123. White, J., Graham, R., & Hay, R. An Investigation into the Oxidising Power of Basic Slags. J. Iron Steel Inst. (London), 131, 91—113, 1935.
124. White, J. Equilibrium at high temperatures in systems containing iron oxides. Iron Steel Inst. (London), Carnegie Schol. Mem., 27, 1—75, 1938.
125. Winchell, A. N. Maghemite or Oxymagnite? Am. Mineral., 16, 270—271, 1931.
126. Wretblad, P. E. Röntgenographische Untersuchungen der Systeme $Fe_2O_3$-$Cr_2O_3$ und $Fe_2O_3$-$Mn_2O_3$. Z. anorg. allgem. Chem., 189, 329—336, 1930.
127. Wyckoff, R. W. G., & Crittenden, E. D. The Preparation and Crystal Structure of Ferrous Oxide. J. Am. Chem. Soc., 47, 2876—2882, 1925.
128. Zachariasen, W. Über die Kristallstruktur von Bixbyite, sowie vom künstlichen $Mn_2O_3$. Z. Krist., 67, 455—464, 1928.
129. Zachariasen, W. Untersuchungen über die Kristallstruktur von Sesquioxyden und Verbindungen $ABO_3$. Skrifter Norske Videnskapsakad. i Oslo I. Mat.-Naturv. Klasse, No. 4, 1928.

# Åsliknande grusryggar i trakten NV och V om Avesta.

Av

ERIK RYTTERBERG.

(Manuskr. inkommet den $^5/_1$ 1943.)

De minerogena jordarterna i trakten av Avesta, där jag under ett flertal år deltagit i Sveriges Geologiska Undersöknings geologiska kartläggning, erbjuda ett drag, som förtjänar omnämnande. Ehuru Avestabladets kartläggning ännu icke är avslutad, har jag erhållit Överdirektör Per Geijers välvilliga tillstånd att lämna ett meddelande härom.

Området ifråga är beläget inom mellersta delen av geologiska bladet Avesta, vars höjdförhållanden i stort framgå av kartan fig. 1. Här uppträder en svärm åsliknande grusryggar av en typ, som tidigare endast i underordnad grad iakttagits men icke utförligare beskrivits. G. Lundqvist har nämligen omnämnt två, med dessa grusryggar jämförbara bildningar, av vilka den ena finnes på geologiska bladet Hedemora (SV om Laggarbo, beskr. till bl. Hedemora, sid. 86—87), den andra på geologiska bladet Smedjebacken (NV om Östra Sveten, vid Hälltorpet, beskr. till bl. Smedjebacken, sid. 95).

Före beskrivningen av de åsliknande grusryggarna må dock några ord sägas om de vanliga sedimenten inom trakten.

Områdets normalt utbildade rullstensås är den s. k. Badelundaåsen, som, kommande från trakten Ö om Västerås, kan följas över slättbygderna mot NV till Brunnbäcks färja, där den genomskäres av Dalälven. Den fortsätter vidare uppåt på älvens östra sida, och efter att ännu en gång ha kastat över älven går den genom staden Hedemora för att vid Västerby, ett stycke NV därom, grena sig. En gren, huvudgrenen, går mot V och en annan mot N.

Närvaron av denna dominerande ås sätter i många avseenden sin prägel på landskapet. De många grustagen utmed åsen vittna om ett flitigt utnyttjande av denna tillgång på grus och sand av olika kornstorlekar. Material för vägbyggnads- eller murningsändamål av detta slag, som påträffas på mera avlägsna orter, kan, trots närvaron av grustag på närmare håll, ofta bevisas härröra från denna ås, framför allt

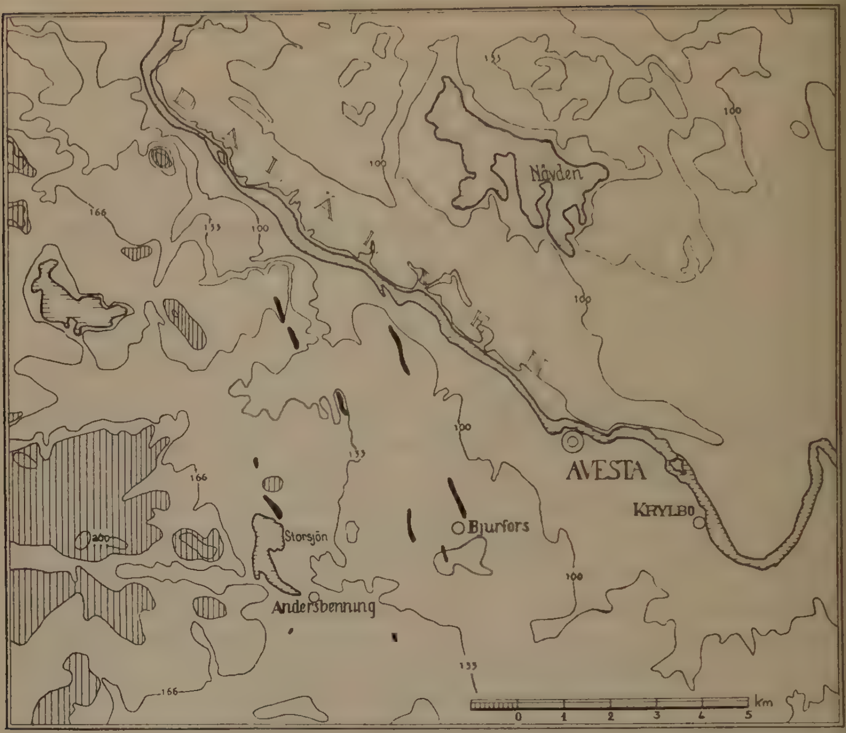


Fig. 1. Området V om Avesta, där grusryggarna (svarta) ligga inom höjdskiktet 130—170 m ö. h. Området över högsta kustlinjen vertikalstreckat. 33-m:s-kurvor efter Rikets Allmänna Kartverk.

på grund av dess höga halt av älvdalsporfyrer men även genom materialets renhet.

Av de finkornigare sedimenten ha svallgruset och sanden en jämförelsevis stor utbredning. Detta är särskilt fallet dels i anslutning till Badelundaåsen, dels inom det ovanligt mossrika området V om Avesta. Svallgruset ligger här i normalt läge på olika nivåer på höjdsluttningar, under det att sanden oftast ligger som utfyllnad i flacka sänkor eller som distalavlagringar till svallgruset. Sanden har även iakttagits som flacka pålagringar på mjälan och moränen samt underlagrande kärr och mossar. Mäktigheten hos dessa sandlager är vanligen ganska ringa, och på sina ställen kunna t. o. m. moränblocken sticka upp genom sandlagret och därmed ge en obestämd och förvirrande bild av markbetäckningens egentliga karaktär.

Grusryggarnas förekomst. De åsliknande grusryggarna anträffas V om Avesta, från Klintboklacken i N till strax söder om linjen Bjurfors—Andersbenning i S och tillhöra i stort sett höjdskiktet

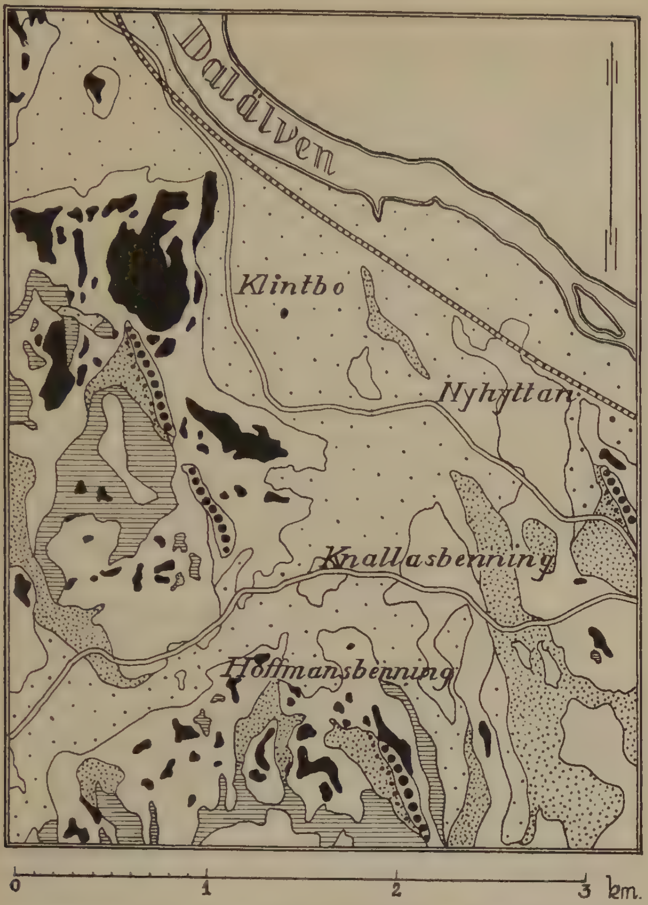


Fig. 2. Grusryggarna SV om Klintbo och S om Hoffmansbenning samt norra spetsen av grusryggen NV om Risbyn. Grov punktrad = grusrygg, tät prickning = sand och grus, gles prickning = mjäla, horisontal streckning = torvmark och svart = berg. Obetecknade områden = morän.

170—130 m ö. h. Deras höjdläge och profiler ha avvägts med Tesdorphs tub och med utgångspunkt från Rikets Allmänna Kartverks fixpunkter.

De flesta av grusryggarna ha en mäktighet, som drager uppmärksamheten till sig. Färdas man på de vägar eller stigar, som vanligen löpa utmed grusryggarnas västra kant, möter man här och var grustag, ibland av mycket imponerande storlek. Andra åter, t. ex. grusryggarna N och SV om Bjurfors (fig. 9), äro mindre betydande och skulle lätt ha förbigåtts vid karteringen och lagts som morän, såvida man ej varit inställd på och medveten om grusryggarnas existens.

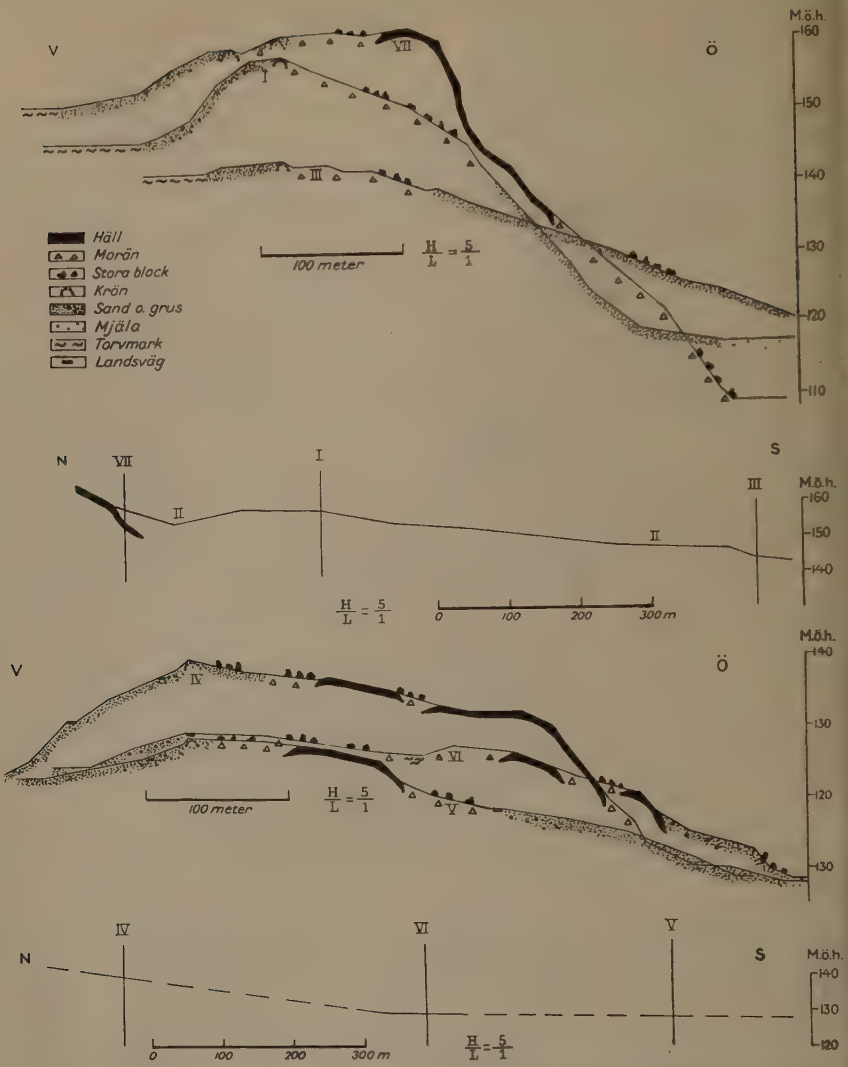


Fig. 3. Profiler över grusryggarna SV om Klintbo (upptill) och NV om Risbyn.

Grusryggarna SV om Klintbo. Vid sydkanten av det högt uppstickande berget Klintboklacken (i norra delen av fig. 2) börjar en grusrygg, som med successivt avtagande höjd fortsätter mot SSO (jämför längsprofilen fig. 3, upptill). Krönet är väl markerat genom sin ryggform och genom sin liksom »stensatta» yta. Man kan därför utan svårighet följa det i, praktiskt taget, ryggens hela längdsträckning mot SSO.

I den allra nordligaste delen av grusryggen, d. v. s. omedelbart söder om och intill berget, står man dock tvekande, ty här är ryggen dels flackt utjämnad och dels finnes här ansats till ytterligare ett krön (profil VII å fig. 3). De båda krönen äro skilda åt av en grund svacka. Det västligaste av de båda är dock det kraftigast utbildade och det som fortsätter mot S.

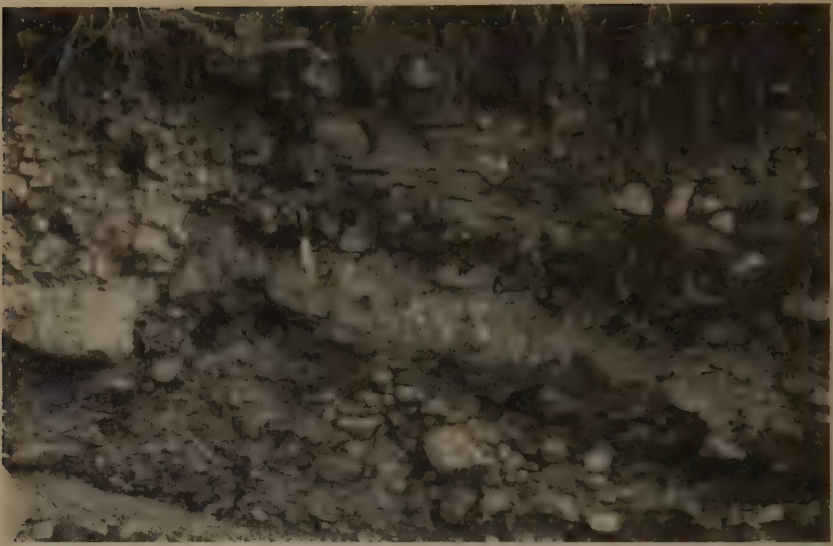
I östra delen av profil VII står berget strax under markytan, varefter det längre mot Ö höjer sig, för att efter hand ersättas av blottad häll, som bildar underlaget till ett mot SSO fortsättande höjdparti. Grusryggen ligger alltså V härom och övergår längre mot V i ett grus- och sandfält, vars största utbredning är mot NV. Här finnes också stora grustag med en avtagande kornstorlek (från grövsta grus till mosand) från Ö till V.

Efter ett kort uppehåll på 200—300 meter dyker en ny grusrygg upp och fortsätter i exakt samma riktning som den förra, mot SSO. Denna södra rygg ligger på något lägre höjd än den norra, vilket framgår av profil III, vilken är dragen över norra delen av denna södra grusrygg (jfr fig. 12).

Huruvida dessa nu nämnda norra och södra ryggar skola betraktas som två olika grusryggar eller som skilda partier av en genomgående grusrygg är svårt att avgöra. Moränpartiet dem emellan är, topografiskt sett, en direkt fortsättning mot S av den sakta sluttande norra grusryggen, fastän karaktären av morän här är övervägande. Sydspetsen av den södra grusryggen är, beträffande sin ytform, svagt markerad och tonar så småningom helt ut i den omgivande moränterrängen.

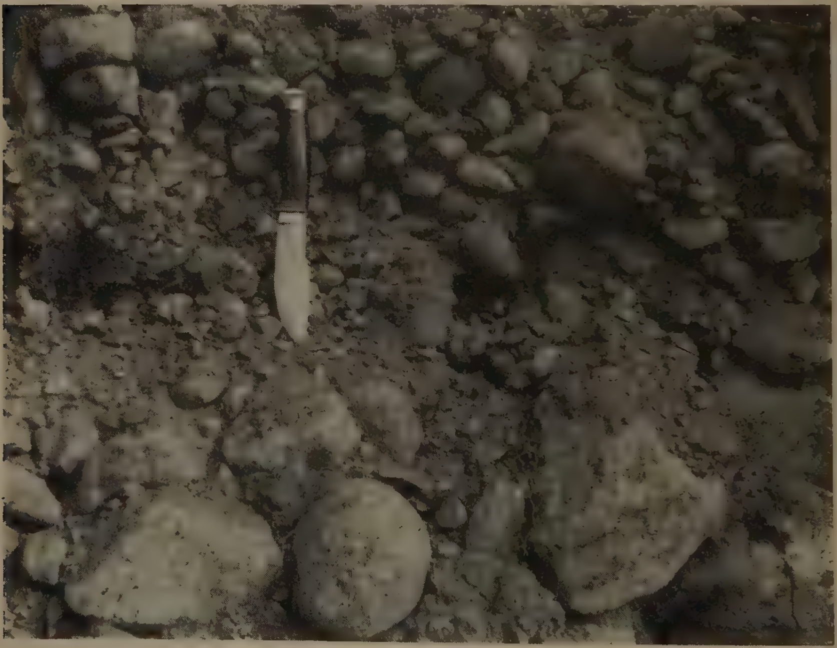
Grusryggen NV om Risbyn. Vid vägskälet, där vägen västerut mot Knallasbenning tar av från stora landsvägen Risbyn—Klintbo (längst i Ö på fig. 2) ligger krönet av den grusrygg, som här benämnes »NV om Risbyn». Riktningen är, liksom hos den föregående, NNV—SSO. Mittpartiet av grusryggen är (som synes på profil VI, fig. 3, underst) mycket flackt, men visar dock sammanhang med den utpräglade krönbildningen N och S därom (profilerna IV och V i samma figur.) Den sydligaste av de tre tvärprofilerna (profil V) anger, att den egentliga ryggformen här nästan upphört, och grusryggen framträder här blott som ett tämligen otydligt krön med brant stupning mot V.

Utefter hela västsidan av grusryggen ligger ett grus- och sandfält, som har sin största utbredning mot NV. Största mäktigheten av gruslagren ligger emellertid vid ryggens norra spets. Här finner man även ett större grustag med goda skärningar. Fig. 4 visar således ett snitt genom lagerserien med konkordanta lager av grövre och finare material, med stupning mot V.



G. Lundqvist 1941.

Fig. 4. Skärning i nordspetsen av grusryggen NV om Risbyn. Konkordanta lager av omväxlande grovt och fint material stupande mot V.



G. Lundqvist 1941.

Fig. 5. Skärning i grusryggen NV om Risbyn (samma som fig. 4). Stenlager.

Figur 5 är en detaljbild från ett stenlager i ovanstående fig. 4. Man lägger här märke till blockens tilltagande storlek nedåt, stenlagrets täthet och blockens och stenarnas rundning, som här snarare torde kunna kallas kantnötning.

Grusryggen V om Gåsmyrberget. Omedelbart SV om och intill Gåsmyrberget (största hällen i mitten av fig. 6) ligger en grusrygg, som endast i sin södra del (profil VIII, fig. 7, upptill) uppvisar den karakteristiska ryggformen. Norra delen av grusryggen ligger tätt sluten till och i lä om det dominerande berget.

Krönet är ej heller så tydligt markerat, som fallet varit med de två nyss nämnda grusryggarna, men i övrigt visar ryggen många likheter med de föregående. Således finner man även här utmed ryggens västsida ett grus- och sandfält, som tilltar i såväl bredd som djup mot NV. Mäktigheten av grusfältet når sitt maximum vid norra spetsen av grusryggen, där man, som väntat, finner ett stort grustag. Sedimentpacken är även här väl skiktad med stupning mot V och NV (fig. 8).

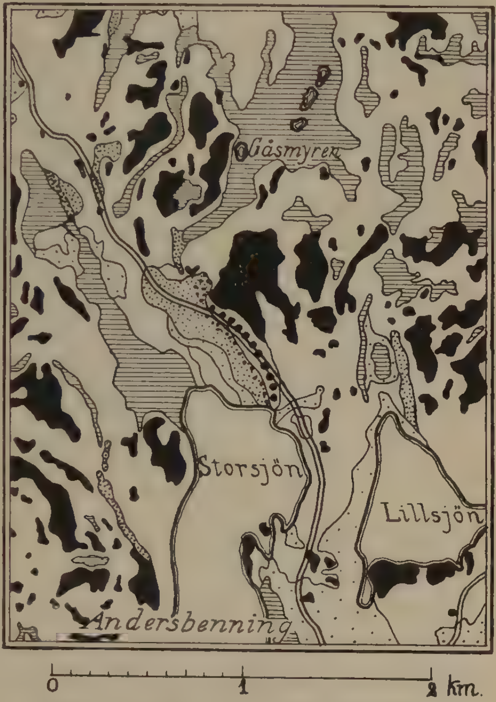


Fig. 6. Området kring grusryggen V om Gåsmyrberget. Samma beteckningar som i fig. 2.

Strax norr om grusryggens mitt finnes en tvärgenomskärning (porten in till kvartsbrecciestenbrottet). Detta är den enda skärning, som påträffats genom mellersta delen av någon grusrygg. Materialet består här nästan uteslutande av block, tätt packade, något avrundade och lagrade nästan direkt på fasta berget.

Profil IX (fig. 7) visar den jämna, grusiga sluttningen mot V, och i östra delen av samma profil, på ungefär 165 m:s höjd ö. h., synas tre mycket väl utbildade strandvallar med riktningen OSO—VNV.

Den nordligaste profilen (profil X i fig. 7) är dragen över norra spetsen av grusryggen, där denna sluttar brant mot N. De trappstegsformade avsatserna här äro vackert utbildade strandterrasser.

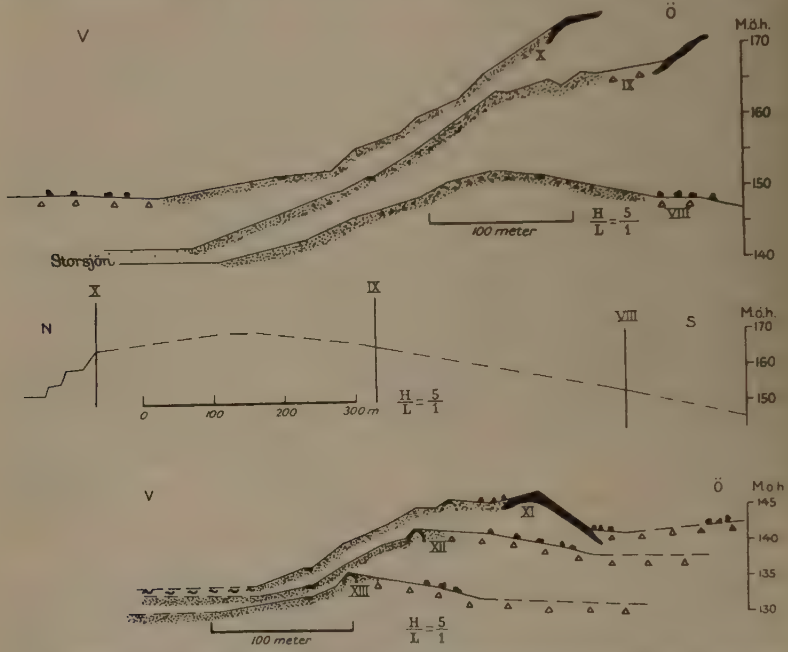


Fig. 7. Profiler över grusryggarna V om Gåsmyrberget (upptill) och SO om Bredmossen. Samma beteckningar som i fig. 3.

Grusryggen SO om Bredmossen. Från höjdpartiet, som markeras av hällarna vid sydöstra hörnet av Bredmossen (fig. 9), sträcker sig en grusrygg med nästan rakt sydlig riktning. Riktningen är något avvikande i jämförelse med de övriga grusryggarna, vilket emellertid får sin förklaring å sid. 14. Som framgår av tvärprofilerna (fig. 7, under) har den en ganska tydligt markerad ryggform, och dess läge i terrängen motsvarar till fullo de ovan beskrivna grusryggarnas, nämligen S och SV om den i norr uppstickande hällen samt i övrigt på västsidan av en moränhöjd. Krönet av ryggen är tydligt utmärkt, såväl genom sin form som genom klapperstensättningen i ytan. Längsprofilen utmed krönet visar en successivt avtagande höjd mot S.

Utmed ryggens västra sida utbreder sig ett grus- och sandstråk, som i detta fall sammanflyter med de stora sandfälten i den omgivande terrängen. Vid norra spetsen av ryggen ligger ett mycket stort grustag, varifrån bilden, fig. 10, är tagen. Stupningen hos skikten övergår från

G. Lundqvist 1941.

Fig. 8. Skärning i norra spetsen av grusryggen V om Gåsmyrberget. Bilden tagen mot NV.

att på västsidan av grusryggen vara rakt västlig till rakt nordlig på norra delen.

Grusryggen S om Hoffmansbenning. Denna rygg, vars läge framgår av fig. 2, har ej blivit höjdavvägd, framförallt beroende på det långa avståndet till närmaste fixpunkt. I stort sett ligger den emellertid på samma nivå som de övriga grusryggarna. Till sin form, riktning och allmänna belägenhet avviker den på intet sätt från de ovan beskrivna. Den ligger alltså S och SV om ett högre hällparti och har ett mycket tydligt markerat, »stensatt», krön.

Grusryggen N om Bjurfors. Detta är en nästan »friliggande», c:a 1 km lång grusrygg (fig. 9). Till formen är den svagt välvd, och där den är som mäktigast är den endast 2—3 m hög. Endast några smärre grustag finnas utmed ryggens västra sida. Dess nordspets har avvägts till 144.8 m ö. h. under det dess sydspets (d. v. s. vid dammen vid Bjurfors herrgård) ligger på 122.3 m ö. h. Ryggens sluttning mot S är alltså relativt svag, endast 22.5 m på 1 km.

Grusryggen SV om Bjurfors. Som de flesta andra grusryggar ligger även denna på västsidan av och i lä om ett höjdparti (fig. 9). Dess utsträckning i längd är relativt obetydlig, och dess nordspets har avvägts till 135.9 m ö. h. Större delen av grusryggens material är redan bortfört, men några grustag vittna nu om ryggens ursprungliga sträckning.

Grusryggarna Ö om Dammsjön och SV om Andersbenning. Båda dessa äro mycket små, endast omkring 100 m i längd (jfr fig. 12). I likhet med närmast föregående grusrygg äro även dessa till övervägande del tömda på sitt material och stora grustag ange nu blott, vad som en gång funnits. Till såväl form som läge uppvisa de fullständig överensstämmelse med samtliga tidigare beskrivna ryggar.

Sammanfattning. Av här föreliggande material att döma tyckas grusryggarna ifråga om deras belägenhet uppvisa flera gemensamma drag. Således 1) ligga samtliga grusryggar alltid på västsidan av ett höjdparti, 2) som regel finnes alltid ett kraftigt hällparti vid ryggens nordspets samt 3) väster om grusryggen ligger ett grus- och sandfält, vars utbredning delvis är beroende av höjdförhållandena inom angränsande område, men vars huvudsakliga sträckning är mot NV.

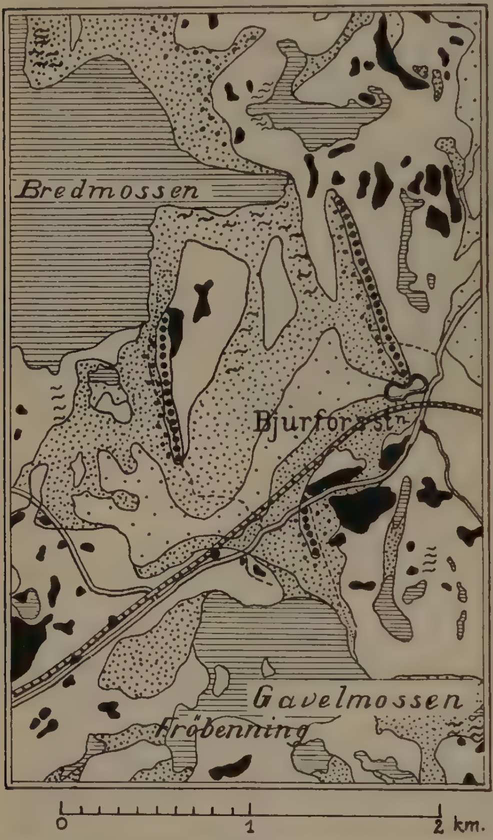
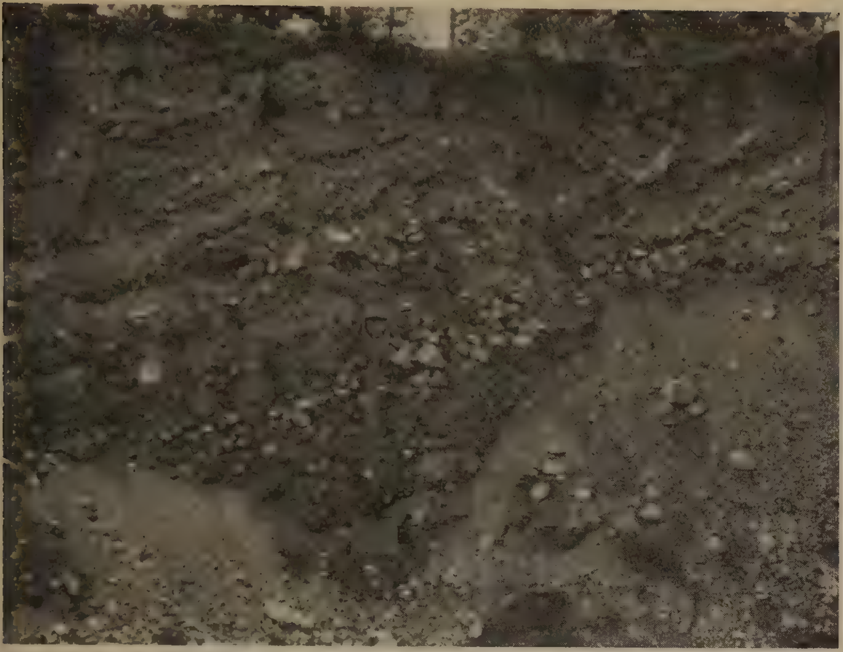


Fig. 9. Området kring Bjurfors med grusryggarna SO om Bredmossen, N om Bjurfors och SV om Bjurfors. Samma beteckningar som i fig. 2.

Beträffande en grusryggs byggnad måste åtskillnad göras mellan norra och södra delen av densamma. Nordspetsen ligger således, som nyss nämnts, alltid »i lä», SV eller S om ett höjdparti, en kraftigt uppskjutande häll (fig. 11 A), under det att södra delen som regel är »friliggande» (fig. 11 B). Grusryggens översta parti är utbildat som ett åskrön, liksom »stensatt» med rundade (klapper-)block, i detta hänse-



G. Lundqvist 1941.

Fig. 10. Skärning i grusryggen SO om Bredmossen. Bilden tagen mot N, stupningen alltså mot NV.

ende likt krönen på de vanliga rullstensåsarna. Krönet är också, som regel, skarpt begränsat och markerat samt visar stark uthållighet, varför man obehindrat utmed detta kan följa grusryggen i hela dess längdsträckning. Den successivt avtagande höjden från N till S framgår av längsprofilerna i fig. 3 och 7.

En återblick på samtliga grusryggar visar även, att de avtaga i storlek och mäktighet från norr till söder. De små grusryggarna Ö om Dammsjön och SV om Andersbenning äro således helt obetydliga i jämförelse med den nordligaste, SV om Klintbo, vilken är den ojämförligt starkast utbildade.

En jämförande översikt av avvägningsdiagrammen visar, att samtliga ryggar ligga under högsta kustlinjen (som, enligt uppgift av G. Lundqvist, finns i dessa trakter på 190—191 m ö. h., jämför kartan fig. 1). Respektive grusryggars högsta punkter, d. v. s. krönet på nordspetsen, variera mellan c:a 170—135 m ö. h. Profilerna över grusryggarnas sydspetsar visa en motsvarande variation från 152—122 m ö. h.

Det vatten, som på sin tid stått över området, har lämnat tydliga spår efter sig i form av strandterrasser och svallgruskappor. Således visa avvägningsprofilerna för de båda högst belägna grusryggarna, V om Gåsmyrberget och SV om Klintbo, en gemensam, kraftigt bearbetad och genom strandvallar markerad zon på 154—156 m ö. h. För de lägre grusryggarna, SO om Bredmossen och NV om Risbyn, kan anmärkas de relativt vanligt förekommande terrasserna på 135—145 m ö. h.

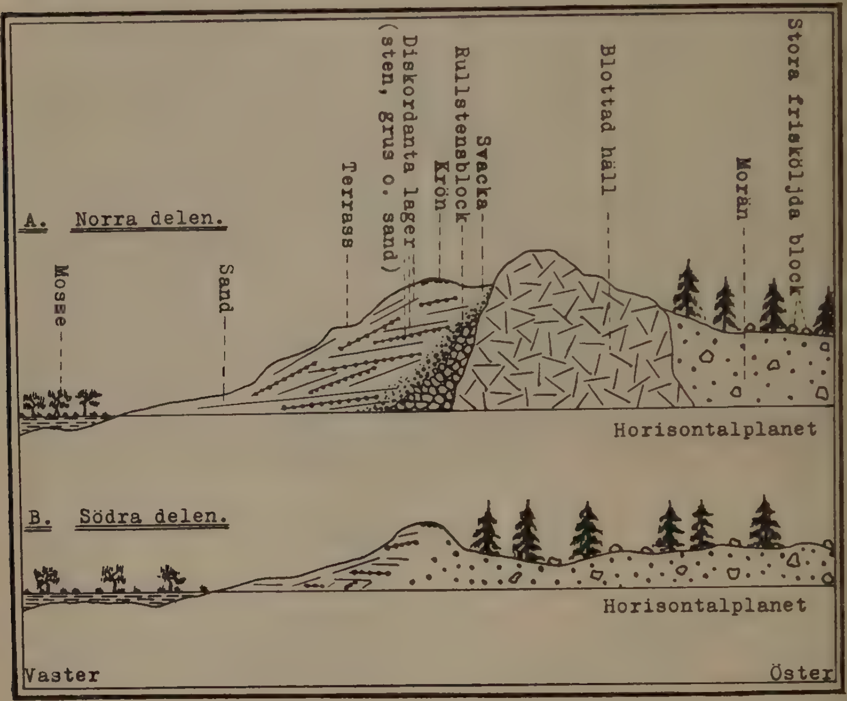


Fig. 11. Schematiska tvärprofiler över grusryggarnas norra och södra partier.

Ett väl renspolat grus på c:a 125 m:s höjd ö. h., väl synligt i ett flertal skärningar, ger också en antydan om en, under någon tid, stillastående nivå av havsytan.

Det må i detta sammanhang omnämnas, att området kring punkt 146 (fig. 12, c:a 800 m S om sydspetsen av grusryggen NV om Risbyn) varit synnerligen kraftigt utsatt för den marina bearbetningen på alla sidor. Man finner här hela serier av strandterrasser, tydligast markerade på nivåerna: 150,8 m, 152,7 m samt 153,4 m ö. h. Högsta punkten i denna avvägningslinje (utmed kraftledningen till Långgruvan) utgjordes av en ytterst kraftigt utbildad strandvall, c:a 3 m hög (Ancylusvallen?), vars övre gräns låg på 153,9 m ö. h.

Även grusryggarnas ostsluttningar visa marin bearbetning på olika

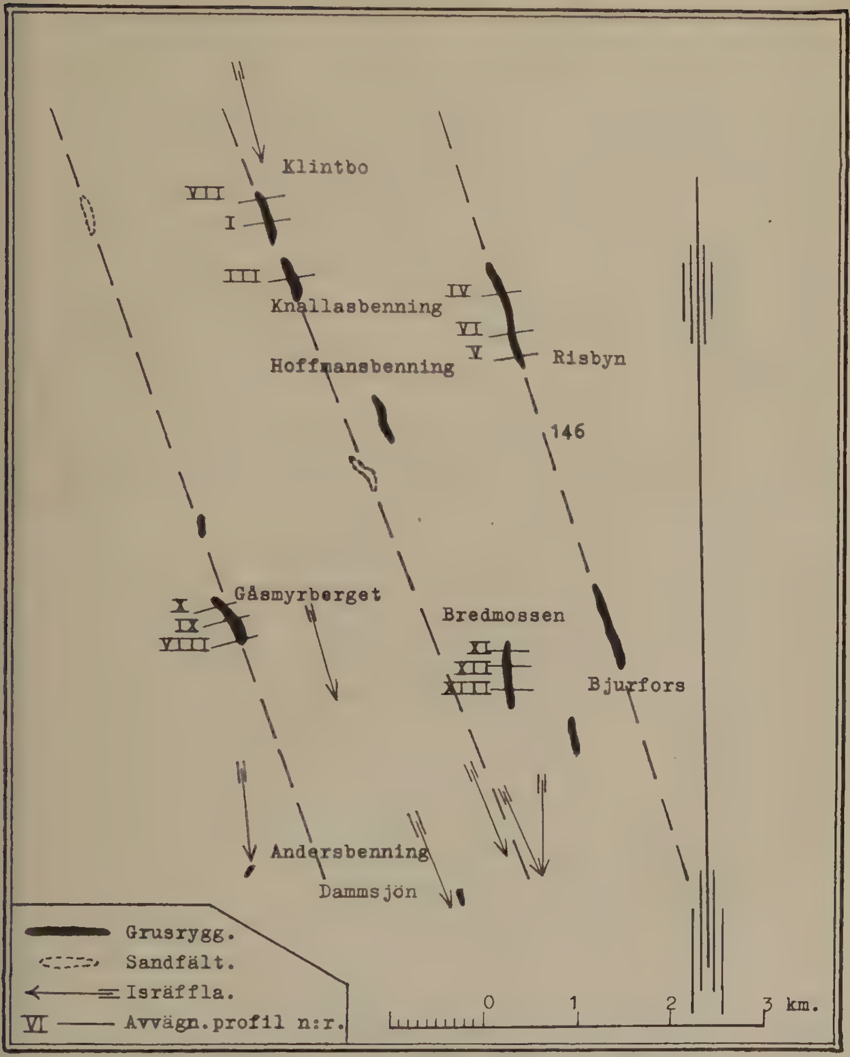


Fig. 12. Överensstämmelsen mellan grusryggarnas och räfflornas riktningar är påtaglig om grusryggarna isoleras.

nivåer, vilka i terrängen stundom ge sig tillkänna genom de däri upptagna grustagen.

Grusryggarnas inbördes läge och samhörighet. På översiktskartan (fig. 1) observerar man svärmen av grusryggar, belägna inom ett relativt begränsat område och, i stort sett, inom ett och samma höjdskikt. Vidare ligga de ordnade i vissa stråk (fig. 12).

Särskilt tydligt framträder detta hos de båda grusryggarna NV om Risbyn och N om Bjurfors. Sammanbindningslinjen dem emellan visar den ihållande, gemensamma riktningen, N 17° V. Det »fria» avståndet mellan dem är c:a 2,5 km. De båda grusryggarna SV om Klintbo uppvisa, som tidigare sagts, en liknande genomgående sträckning, vars riktning är N 20° V. Sammanbindningslinjen dem emellan går, i sin förlängning mot SSO, över ett sandfält (på fig. 12 angivet med en streckad kontur), vars form och allmänna belägenhet ger anledning till förmodandet, att här möjligen legat en grusrygg, om än av ringare mäktighet. Den kan helt och hållet ha varit uppbyggd av finare material och därför tidigt nedbruten. (Det har även tidigare antytts, att en sådan grusrygg, genom sin stundom föga utpräglade ytform, mycket lätt kan undgå kartörens observation.)

På samma sätt har en linje dragits från grusryggen V om Gåsmyrberget mot ett i riktningen N 18° V därom beläget sandfält, vilket likaledes på grund av form och läge förmodas stå i samband med en grusrygg eller eventuellt före detta grusrygg.

Det må synas djärvt, att på så vaga grunder lägga ut en sammanbindningslinje, men riktigheten i detta tillvägagångssätt har senare stärkts, vilket framgår av följande. Under karteringen hade påträffats en mycket liten, »friliggande» grusrygg, c:a 1,5 m hög och endast 30—40 m lång, med riktningen N 18°—20° V. Denna ligger mitt i nyssnämnda sammanbindningslinje på fig. 12 (c:a $^3/_4$ km NNV om nordspetsen av grusryggen V om Gåsmyrberget).

Sammanfattningsvis kan sägas om riktningen hos dessa grusryggar, eller rättare deras sammanbindningslinjer, att de avvika 10°—24° mot V från nordlinjen (jfr fig. 12). Denna riktning sammanfaller i stort med påvisade räffelriktningar inom området.

Grusryggen SO om Bredmossen har emellertid, som tidigare anmärkts, en från övriga ryggar avvikande riktning, nämligen N—S. Det nyss framförda påståendet om grusryggarnas samhörighet och uppträdande i raka stråk behöver emellertid fördenskull ej falla. Ty, som framgår av fig. 12, finnes, c:a 1,8 km S om grusryggens sydspets, en räffelriktning i rakt N—S inlagd, vilket må gälla som bevis för påståendets riktighet, även när det gäller detaljer.

Fåtaligheten i räffelobservationerna torde bero på de ur denna synpunkt otjänliga bergarterna, vanligen grova urgraniter, pegmatit och kvartsit samt mycket grov leptitgnejs. Här nedan följer förteckning över de i fig. 12 upptagna räffelriktningarna:

| Lokal. | Räffelriktning. |
|---|---|
| Klintboklacken | N 12° V. |
| Södra stranden av Lillsjön (jfr fig. 6) | N 12° V. |
| I kraftledningen, 2,5 km SV om Bjurfors | N 18° V. |
| I grustag, » » » » » | N—S (yngre).<br>N 24° V (äldre). |
| Södra stranden av Dammsjön | N 22°—24° V. |
| Vid landsvägen, 800 m SV om Andersbenning | N 10° V. |

Grusryggarnas bildning. Huru dessa grusryggar bildats är en fråga, som endast kan besvaras med hypoteser, grundade på iakttagelser av såväl grusryggarnas byggnad i detalj som dess utformning i stort.

Med stor sannolikhet ha grusryggarnas nuvarande form uppstått genom en utveckling i minst två faser. Primärt har alltså materialet avlastats på platsen, och sekundärt har det omlagrats till den form grusryggen nu har.

Först och främst måste så närvaron av den avsevärda mängden material (block, grus och sand) förklaras. Ett försök att i dessa grusryggar se en variation till rullstensåsarna, ger ej någon fullt tillfredsställande förklaring. Till förmån för en sådan teori talar emellertid ryggarnas uppträdande i raka stråk, som det framställts på fig. 12, samt det åslika krönet. Krönets avtagande höjd mot söder *kan* vara resultatet av en sekundär omlagring, varvid grusryggens södra del, genom sitt i Ö oskyddade läge, blivit mera påverkad än norra delen. Stridande mot detta antagande står dock det faktum, att blockmaterialet som regel ej är rundat till den grad, som är vanligt i åtminstone de större rullstensåsarna. Detta skulle dock kunna förklaras genom en kortare transport. Det kanske mest kännetecknande för vissa av de större rullstensåsarna i Bergslagen är ju dess innehåll av Älvdalsporfyrer. Block av detta slag ha även anträffats (och då, som väntat, mycket mera rundade än angränsande block av annan bergart i samma lager), men i en mycket låg frekvens. G. Lundqvist lämnar här vid förfrågan den uppgiften, att Älvdalsporfyrerna förefinnas spridda i moränen i dessa trakter, ända upp till en halt av 5 % (jfr beskr. till bl. Hedemora, sid. 79).

En blick på detaljkartorna (figurerna 2, 6 och 9) visar en del sand- och grusstråk i isrörelseriktningen, som enligt min mening måste ses i samband med bildningen av grusryggarna. Dessa grus- och sandstråk, vanligen mycket flacka pålagringar på mjälan och stundom underlagrande mossar och kärr, kunna inte vara annat än resultatet av mer eller mindre omfattande vattenspolningar från norr mot söder i stort sett. I vissa områden (ex. Ö och SO om Bredmossen) måste sanden betraktas som distalmaterialet efter spolningar från öster mot väster. Området i sin helhet uppvisar också tämligen allmänt spår av spolning. Därtill måste hällen, som ständigt återfinnes vid nordspetsen av grusryggen, tillmätas en viss betydelse, i det att den, genom sitt läge, möjliggjort avlastningen av sedimentmassan just där.

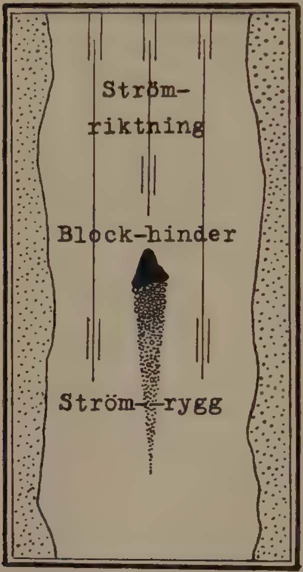


Fig. 13. Schematisk bild åskådliggörande uppkomsten av en strömrygg.

Förutsätter man alltså kraftiga vattenströmmar, emanerande från en, mer än vanligt kraftig, avsmältning av ismassan, eller kanske rentav som plötsliga tappningar från isdämda sjöar, forsande mot S, får man en godtagbar förklaring till de flesta av de företeelser det här gäller. Grusryggarna skulle i så fall vara de stora motsvarigheterna till de små strömryggar, som man så ofta möter i bäckar med isynnerhet grusig och sandig botten. Företeelsen kan åskådliggöras med fig. 13. Blocket — hindret motsvaras då av den i grusryggens nordspets uppstickande hällen. En dylik strömrygg besitter även den egenskapen, att den är högst och kraftigast utbildad ett stycke bakom hindret och efter hand avtagande i såväl höjd som bredd ju längre bort man kommer från hindret, tills den så småningom helt tonar ut i omgivningen (jfr längsprofilerna i fig. 3 och 7). Strömryggföreteelsen är till alla delar möjlig att anpassa på grusryggarna, och som den till synes kan ge förklaring på åtminstone flertalet av hithörande frågor, får den i fortsättningen utgöra min förklaring till grusryggarnas primära sedimentation.

Materialets överspolning åt väster. Samtliga tvärprofiler visa, att grusryggarna, som tidigare nämnts, äro belägna på västsidan av ett högre häll- eller moränparti, åtminstone gäller detta deras norra delar. Sydspetsarna äro, som sagt, ofta friliggande, d. v. s. ej bundna till något motsvarande höjdparti i Ö.

Ostsidan av grusryggen är vanligen utbildad som en flackt sluttande »stötsida», västsidan däremot som en mera brant stupande »läsida». Någon samhörighet mellan de av R. Sandegren, på geologiska bladen Gävle och Storvik, påvisade yngre ändmoränerna och här beskrivna grusryggar existerar dock knappast, trots vissa överensstämmelser i såväl form som riktning. Ändmoränerna ha, sannolikt med goda skäl, fått tillnamnet morän, därmed inneslutande allt, som begreppet omfattar, under det att materialet i grusryggarna, dels på grund av sin frihet från de minsta kornstorleksfraktionerna och dels med tanke på dess nötning och rundning, måste förutsättas ha glacifluvial extraktion.

Orsaken till denna osymmetriska form torde vara att söka i en sekundär omlagring, varvid materialet spolats över åt V av ostliga strömmar. Härvid har det grövre materialet, blocken, kommit att ligga närmast nedanför branten (fig. 11) medan de finare fraktionerna spolats längre ut åt V. Största utbredningen av sandfälten ligger ju som regel NV om grusryggen, varjämte de här nå sin största mäktighet. De största grustagen ligga ock vanligen vid eller strax NV om ryggens nordspets. Stupningen av lagren är likaså övervägande mot NV, varför det kan anses fastslaget, att den kraft, som åstadkommit överspolningen, med större noggrannhet uttryckt, haft riktningen SO—NV. I de allra nordligaste delarna av grusryggarna och de till dem hörande utströmmade grus- och sandskikten finner man även en lagerställning med stupning mot N. En sådan stupning av skikten kan endast ha åstadkommits av strömmar, som gått nära nog parallellt med grusryggen.

Denna överspolning synes ha varit mycket oregelbunden i sin intensitet att döma av de omväxlande, konkordanta sten-, grus- och sandlagren samt de här och var uppträdande blocksporrarna. Även diskordanser ha påträffats i lagerserierna. Helt oskiktade blockpackar tyda också på en tidvis ytterst kraftig och plötslig sedimentation.

# Isdelarstudier vid polcirkeln.

Av

ERIK LJUNGNER.

## Inledning.

(MS. inkommet 26 3. 1943.)

Som första utgångspunkt för den skandinaviska nedisningen har man givetvis måst antaga en sådan lokalglaciation, som i nutiden utmärker de västliga högfjällen. Men i och med lokalglaciationens utväxande till en begynnande allmän nedisning antages högfjällens ostsida ha blivit den viktigaste ansamlingsplatsen för snö- och ismassorna, och här utbildades isdelaren. En teoretisk grund för denna uppfattning gavs av Enquist, som på den skandinaviska halvöns profil konsekvent tilllämpade sin viktiga och allmängiltiga erfarenhet om glaciärernas orientering på bergens läsida. (Enquist 1916 s. 34 ff.)[1]

Att isdelaren varit underkastad vissa vandringar, har framgått ur blockspridningen. Allmänt antages en vandring åt öster, enligt flera forskare efterträdd av en åt väster. Men angående omfattningen av förflyttningen och tidsförhållandena därvid gå meningarna fortfarande mycket isär. Den av Enquist (1918 s. 23) försiktigt uttalade meningen, att isdelaren sannolikt förflyttade sig österut ända till Bottniska viken, vilken energiskt bestreds av G. Frödin (1925 s. 185), hävdas nu med bestämdhet av Ahlmann, Laurell och Mannerfelt (1942 s. 22). I läroboken Sveriges geologi (1936 s. 144 och 177) uttalar däremot Granlund — efter att ha bekräftat, att isdelaren på grund av rikare snöackumulation alltid legat på östsidan av den skandinaviska höjdryggen — att förskjutningen ägt rum inom en snäv ram, nämligen från sjökedjans ostliga till dess västliga begränsning. Vandringen åt öster förlägges än till avsmältningstiden (Tanner 1915, Sauramo 1931), än till tillväxttiden (Enquist 1918, Ahlmann et al. 1942). Viktigare data ha lämnats för Lappland av bl. a. De Geer (1888), Fredholm (1891 och 92), Hamberg (1909), Gavelin (1906 och 1909), Sjögren (1909), J. Frödin

---

[1] I olikhet med Enquist kan jag icke finna, att hans teori *ersätter* Högboms tes från 1885 om isdelaren som ett jämviktsläge för ömsesidigt motstånd. Sistnämnda är en naturlag, med vilken varje användbar teori måste vara förenlig. Denna precision spelar en roll för det följande.

(1914), Tanner (1915) och Geijer (1922), för Jämtland och Härjedalen av Durocher (1846), Hörbye (1857), Törnebohm (1872), Högbom (1885, 1920), Caldenius (1909) och G. Frödin (senast 1925). Den senaste kartografiska sammanställningen över refflorna och (sista) isdelaren har meddelats av Lundqvist (1942).

På grund av uppdrag från Bolidens Gruvaktiebolag har jag fått tillfälle att — vid sidan av andra uppgifter — ägna ett studium åt denna fråga i vad gäller fjällkedjans profil utefter Laisälven och delvis Skellefteälven. Undersökningarna äro icke avslutade. Särskilt återstå undersökningar angående isdelarens östligaste läge. Men såsom resultat framstå dock redan, att isdelaren under ett tidigt, långvarigt skede legat långt västerut i fjällkedjan, i närheten av vattendelaren, samt att isdelarens förflyttning från sitt senare, östliga läge emot fjällen kunnat successivt följas fram till dödisstadiet. Förstnämnda resultat, som överensstämmer med mina rön från Anderna, medför ett nytt perspektiv på nedisningens utveckling och låglandsöversvämningens orsaker. Då isdelaren utgör läget för ismassans balans mellan öster och väster, så måste varje isdelarläge avspegla en viss utbredning av ismassan. Isdelarens västliga läge svarar mot en ostlig iskant ungefär vid sjökedjan, som därvid kan förklaras på samma sätt som de patagoniska randsjöarna — som glaciala bäcken utbildade vid randen av en ur fjälldalarna framskjutande isfront och på sin tid förstorade genom dämmande ändmoränbågar. Dessa konnektioner behandlar jag i uppsatsen »East-West-Balance of the Quaternary Ice Cap in Patagonia and Scandinavia» (under tryckning). På denna plats vill jag inskränka mig till en enkel redogörelse för de gjorda iakttagelserna och de omedelbara resultaten och tackar ledningen för Bolidens Gruvaktiebolag för tillståndet att publicera densamma, främst direktör O. Falkman.

## Metodik.

Min undersökning grundar sig i huvudsak på hällskulpturen. Blocken kunna icke ge någon kronologi, om man inte finner skärningar med strängt åtskilda bäddar, vilket är otänkbart i jungfruliga områden och även annorstädes sällsynt.

Vid hällanalysen utnyttjar jag mina erfarenheter från Bohuslän angående förhållandet mellan ismäktighet och skulpturform. En mäktig is är plastisk och skulpterar även i »utförsbackarna». En tunn is är spröd och lägger hela arbetet på upphöjningarnas över- och uppströmssidor, skapande den språngbrädesliknande profil, som är känd från Uppsala- och Stockholmstrakten, senast genom Sahlströms vackra studie 1914. Analysen ger alltså upplysning inte bara om åldersförhållandet mellan

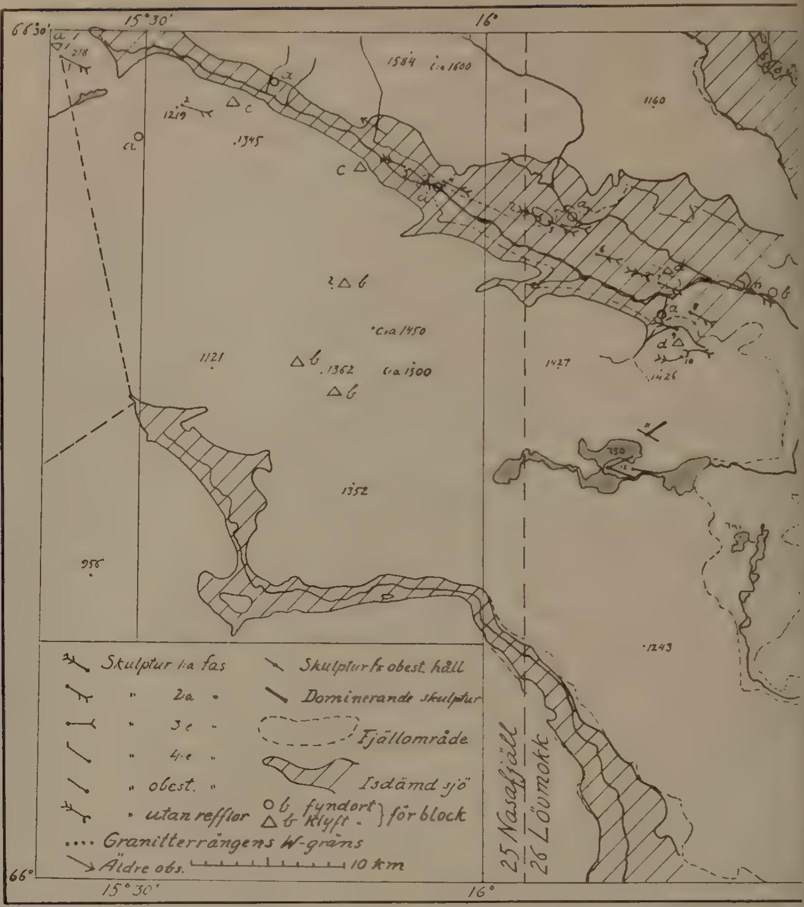
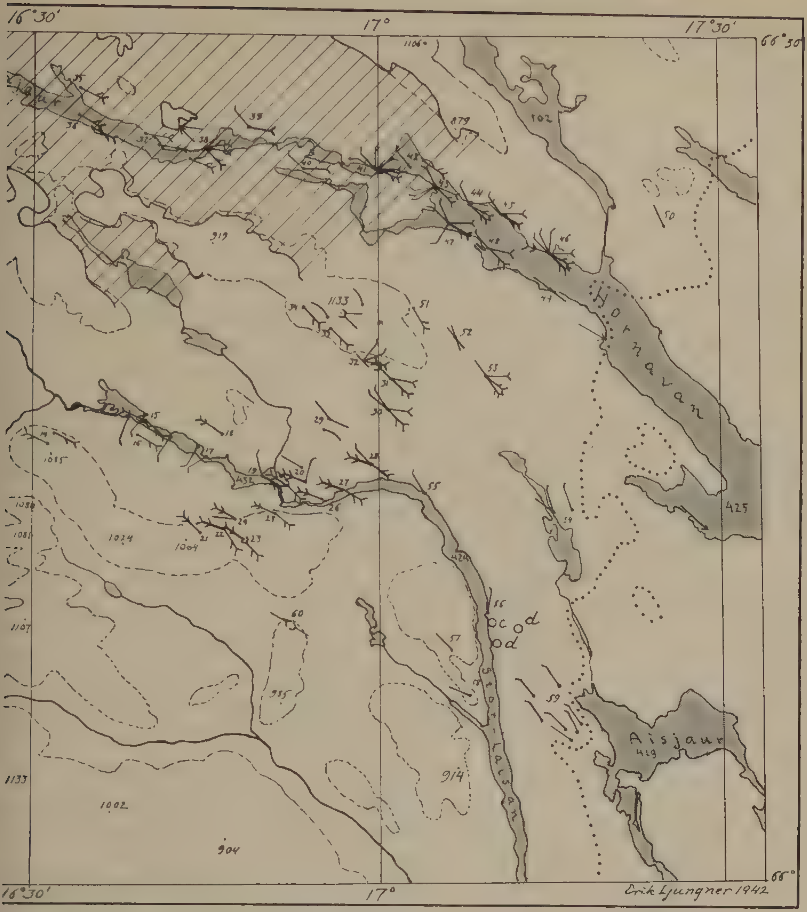


Fig. 1. Isrörelserna å topografiska bladen

strömmarna (kronologisk analys) och den relativa varaktigheten av olika strömmar (kvantitativ a.) utan också om den skulpterande isens plasticitet (kvalitativ a.) som ger relativa mäktigheten. Dessa förhållanden behandlas i mitt arbete Spaltentektonik etc. del III: 2 (under tryckning). För att säkert undvika förväxling mellan uppströms- och nedströmsrefflor och för att kunna avläsa den skulpterande riktningen även i hällar med bortvittrad slipning och reffling använder jag mig av olika tvärfrakturer benämnda »parabelriss» och »Sichelbrüche» (se del III: 1 av nyssnämnda arbete s. 287 fig. 123). För att bestämma åldersförhållandet mellan tvenne reffelriktningar, som bilda 180° vinkel, brukar jag undersöka avslipningsriktningen för mindre ärr i neutralt lutande yta.



Nasafjäll och Löfmokk. Skala 1 : 500 000.

En särskilt lycklig omständighet ligger i traktens växlande berggrund, särskilt inom zonen för isdelarens senaste lägen, där de bevarade rörelseriktningarna äro många. Lerskifferhällarna ge med rika detaljer avsmältningsskedet, angränsande kvartsithällar ge knapphändigare men delvis mycket äldre data. Dess parabelriss gå tillbaka ända till nedisningens första skede.

Endast med iakttagande av nämnda förhållanden torde det vara möjligt att närmare utreda kronologien i ett isdelarområde.

Kartans tecken för skulpturriktning äro försedda med 1—4 faner, varvid 4 beteckna första rörelsefas, 1 sista. Omkastningen i förh. till tidsföljden har skett med tanke på plasticiteten, som från 2:a rörelsefasen är avtagande. Issjöarna äro inlagda efter Gavelin (1910).

Över traktens berggrund föreligga översikter av Svenonius (1895), Holmquist (1900), Holmsen (1832), A. Högbom (1937) och Kautsky (1940).

### Isströmningen enligt skulpturen.

Inom Nasaissjöns område och på omgivande fjäll ha urskilts två skulpturer, en äldre från WNW och en yngre från ESE. W om 16° 15′ härstamma observationerna från en snabbtur, varför endast fåtaliga lokaler kunnat besiktigas. Tecknet i lokal 1 hänför sig till Nasafjällets toppplatå (jfr Fredholm 1891 s. 446 och 1892 s. 196), i nr 2 till 1 166 m höjd i Kargasatåive. Under nr 3 ha sammanförts två hällkomplex på c:a 200 m avstånd, vilka båda vackert uppvisa den dubbelsidiga skulpturen i ungefär lika utveckling, om hänsyn tages till att den i allmänhet västfallande strukturen något gynnar skulpturarbetet för isströmmen från vattendelaren (1:a fasen). De mot WNW vända stötsidorna äro nämligen här de mest framträdande. Tvärfrakturer kunde alltid erhållas till kontroll av strömriktningens håll. Bibehållna issjöstrandliner och åt WNW stupande marginalterrasser (se Gavelin 1910 s. 64) samt bibehållna åskullar av mellansvensk submarin typ ända nere vid hällkomplexen bekräfta, att rörelsen från ESE är den yngsta av de två.

Ett par km SE om nämnda hällkomplex sänker sig dalbottnen i tvärt fall ned under skogsgränsen, och hällar i dalbottnen bli svåråtkomliga. I lokalerna 6, 8 och 13 påträffade hällar visa dock, att skulpturen från ESE är den härskande. Det är också fallet i hela ESE-sluttningen av fjället Huorras, lokal 5, vars bevarade veckstruktur erhållit en överskärande tryckskiffrighet med glimmer stupande åt WNW. På toppen (1 004 m ö. h.) ge de åt WNW vettande vittrade rundhällarna bestämt intryck av isskulptur från nämnda håll, men en kontroll medelst tvärfrakturer medgav icke tiden, varför tecknet utförts med reservation.

Så mycket rikare kontroll erhölls emellertid i kvartsitskifferfjällen under 16° 15′ längd. På nordsidan Laisan (här omkring 498 m ö. h.) reser sig öformigt i dalen det låga fjället Plassavardo, lokal 7, c:a 785 m ö. h. En tunn, flackt mot W stupande bankning parallell med strukturen har möjliggjort för ESE-strömmen att blada upp berggrunden och därmed förstöra äldre hällar med 1:a rörelsefasens skulptur. Ännu i toppen ser man endast 2:a fasens skulptur. Men ett stycke väster därom, på 757 m ö. h., bilda lagren lokalt en synklinal med åt SE stupande veckaxel. Där finnas stötsidor bevarade, som till sin ställning och tydliga tvärfrakturer säkert angiva den 1:a fasens skulptur, från WNW.

Mitt emot Plassavardo reser sig på älvens sydsida fjället Svaipa, 1 426 m ö. h. Dess vita fjällkvartsit, här mera tjockbankad, stupar NW.

Dalsidan är mycket brant, upp till 960 m, där en tydlig trågrand framträder. I trågväggen härskar nertill SE-skulpturen. Från 900 m och uppåt härskar däremot NW-strömmen, och SE-strömmens skulptur, inskränkt till en svag kantavrundning med parabelriss, har jag där kunnat spåra upp till trågranden men — under till buds stående tid — icke längre. Den 1:a fasens skulptur är vacker, så länge hällar finnas. Ovanför 1 000 m har dock froststrängningen haft stor effekt.

På topp-platåns ostsida uppvisar dalsidan en bäckinsänkning, lokal 10, som särskilt på nivåerna 1 325 och 1 057-m bildar framträdande trappsteg, ovan vilka nischlika utvidgningar observeras. Den övre av dessa hyser en perennerande snödriva, den undre, mellan 1 122 och 1 057 m, hällar med skulptur från WSW, troligen från början av fas 1. Två parabelriss visade dock också på en ström i motsatt led, troligen fas 2. På 1 010 m utfylles bäcksänkan av en stor moränterrass tillhörande huvuddalens istunga från SE. — Sistnämnda, i förbigående gjorda observationer anföras här för den upplysning de ge om att istungan saknat näringstillskott från lokalglaciation i Svaipa. På kartan äro reffeltecknen krökta, visande isrörelsens orografiskt betingade deviation.

I nästa fjällsträckning på älvens sydsida, sträckan Tjäksa—Krappesvare, äro förhållandena i stort desamma. I Tjäksas starkt vittrade glimmerskiffer (lokal 14) framträder på höjderna endast den 1:a fasens skulptur, medan den 2:a fasens därjämte är synlig under gynnsamma omständigheter från 820 m nedåt och förhärskande från omkring 700 m.

Fjället Krappesvare (med Kaissetjåkko 1 064 m) uppbygges av NE-strykande vertikalställda bergribbor av omväxlande porfyr, kvartsit, arkos och lerskiffer, en för skulpturstudier idealisk och med hänsyn till 1:a och 2:a fasens rörelser fullt neutral berggrund. Praktfulla äro också rundhällarna i hela fjället, endast i högsta toppområdet skrovliga. NW-skulptur är också det enda man ser utan att göra mycket ingående undersökningar. Delvis med hjälp av spade lyckades jag konstatera den 2:a fasens spår på 778 och 786 m (sammanförda som lokal 22) samt slutligen på 888 m (lokal 23), varför möjlighet torde föreligga att vid grävning finna den i alla nivåer.

I motsvarande älvsträcka äro hällarna dubbelsidiga, med skulptur av 1:a och 2:a fasen. Berggrunden är vid de tre sjöarna en kvartsrik sparagmit med flackt stup mot WNW, vilket delvis förklarar den bättre utbildningen av 1:a fasens hällar. Men även ganska strukturlösa hällar av kvartsit och arkos vid Storlaisans västände visa övervikt för skulpturen av 1:a fas.

Vid de tre sjöarna och särskilt i trakten av Adolfström (vid lokal 15) förekommer såsom sista, kortvarig fas en kraftig reffling av en styvare is från SSW, tydligen kommande tvärs ned från nyss behandlade fjällrygg. Denna isström torde från den låga bergryggen på älvens SW-sida ha transporterat det imponerande blockhav, Hålsten, som avstänger Adolfström från älven. Blocken ligga på oförstörda glaciala hällar men äro själva brottstycken av glaciala hällar och överensstämma petrografiskt med den mera rena sparagmiten på älvens sydsida. I förhållande till närmast äldre reffelriktning är den sista högervridande.

Den motsatta dalsidan stiger sakta upp mot Peljekaisseryggen (1 133 m). Hällar ha måst blottas med spade. Isrörelsen blir efter 2:a fasens slut genomgående vänstervridande, med ett markerat uppehåll i riktning från öster (3:e fas) och därefter via NE svängande över till NW, varvid i vissa hällar den från NW utgående 4:e fasen uppnåtts (säkert i 28 och 30).

Kartområdets bäst blottade hällar finner man, utom i Adolfström, i Hornavan. Nordostsidans hällar ligga under inflytande från den markerade dalsidesluttningen från Rebnisryggen (Rebniskaisse 1 106 m). Här finna vi också — i analogi med Peljekaisses SW-sluttning — den fullständiga vridningsrosen under vänstervridning från 2:a över 3:e till 4:e fas, rikast i den flacka lokal 46, där också hela successionen är klar. I motsatta dalsidan, Peljekaisses NE-sluttning, saknas hällar. Hällarna på Hornavans SW-strand ligga särskilt med hänsyn till sjöns 200 m djupa ränna ännu i NE-sluttning men delvis närmare Rebnisryggen. Vridningen följer fram till 3:e fas samma vänstervridande regim som på sjöns NE-sida. Men i fortsättningen finnas refflor från SW-hållet, visande, att Peljeryggen gör sig gällande. Den slutliga 4:e fasen kan med avtagande effekt följas så långt åt W som till Ringselet (39), där den upphör.

Den frågan uppställer sig nu, om växlingen i vridningens tecken hos hällarna på Hornavans SW:a strand skall tolkas såsom ett växlande inflytande från först Rebnisryggen och sedan Peljeryggen, eller om vridningen fram till 3:e fas har en allmän orsak och är oberoende av detaljorografien. För ett säkert besvarande av frågan skulle man nog önska ett blottläggande av hällar i mera avgjord NE-sluttning eller observationer på flera helt fritt belägna fjälltoppar. Åtskilligt talar emellertid för det senare alternativet. Skulpturen från E utmärkes av en påtaglig beständighet hos isströmmen, gentemot vilken de senare refflorna från SW i NE-sluttningarna och från NE i SW-sluttningarna ha mera episodisk och mindre riktningsbestämd karaktär. På de helt fritt liggande topparna 23 i Krappesvare och 1 133 i Peljekaisse saknas visserligen refflor tillhörande den motfjällsriktade skulpturen, men i sistnämnda punkt visar diabasens parabelriss på isrörelser från väderstreck varierande mellan SE och (huvudsakligen) E. Slutligen är den 3:e fasens rörelse representerad i den helt neutralt belägna lokalen 53.

Den närmast liggande förklaringen till en allmän vänstervridning fram till E finner jag i avisningen på kontinenten och i södra Sverige med åtföljande förskjutning åt N av landisens tyngdpunkt. Isdelarens axel kan liksom ett bergvecks i horisontalplanet avbildas med en linje, men därvid kommer icke fram ett för båda viktigt element — kulminationen. Samtidigt som isdelaren vandrade mot WNW, försköts dess huvudkulmination åt NNE. På Lundqvists karta kan avläsas en mycket framträdande kulmination hos isdelaren strax N om polcirkeln (från polcirkeln och upp till St. Luleträsk). Den gör sig gällande däri, att refflorna få en rörelsekomponent parallellt med isdelaren, i riktning från kulminationen. Denna synes kontinuerligt sänka sig ända till Jämtlandsdepressionen. Lundqvists karta kan på grund av materialet givetvis icke ha någon åldersgruppering av refflorna, men av flera skäl kan åldern för den nämnda kulminationen icke vara mycket lägre än åldern hos vår 3:e fas. En kulmination vid polcirkeln passar just också för denna.

Jag har tänkt mig, att den 3:e fasen, som utmärker ett stillastånd under en intermediär grad av avsmältning (förminskad plasticitet uppenbar) skulle eventuellt motsvara ra-stadiet. Isströmmen synes enligt ovanstående ha överskridit Peljekaisses topp, vilket ger en minimimäktighet av 700 m över Hornavans strand.

Under följande skeden blir beroendet av den lokala orografien uppenbar. Vid själva isdelarpassagen över en punkt, då rörelsen mot- och frånfjälls temporärt inställes, är den mot dalarna riktade komponenten enarådande och åstadkommer tvärrefflorna. Den 4:e fasens starkt avtagande effekt från lokal 46 till lokal 39 i Skellefteälvens dalgång och frånvaro i 38 är ett vackert uttryck för isdelarens vandring motfjälls och för den åtföljande fasförskjutningen längs dalgångarna.

SE om nu behandlade bälte tilltager den 4:e fasens skulptur så kraftigt, att inom Laisdalens fjällskiffrar och sandstenar ingen äldre skulptur framträder. Ett efterforskande i hårdare bergarter skulle troligen uppdaga sådan, då SE-skulpturen i kvartsithällen lokal 46 vid Hornavan ännu är mycket vacker. Reffeltecknet SE därom hänför sig enligt Fredholm (1892 s. 196) till svart skiffer. — I lokal 60 föreligger endast observation från flyg.

Under ett sedan 1939 pågående geologiskt och geofysiskt arbete vid Storlaisan, som geologiskt utgör ett fönster, har den successiva djuperosionen genom de eokambriska sedimenten och delvis ner i granitunderlaget kunnat följas. En icke föraktlig erosion faller på den 4:e fasen. Denna har emellertid arbetat starkt nedbrytande även på granittröskeln vid sjöns utlopp. Stora block ha bortbrutits i så hastigt tempo, att slipningen bara blivit en svag kantavrundning. En redogörelse för dessa undersökningar faller utanför ämnet.

### Den sista isfördelningen enligt avlagringsformerna.

Gavelin har (1910 s. 62 och 64) omnämnt åt NW lutande israndbildningar i övre Laisdalens sidor såsom spår av den istunga, som från SE sköt upp genom dalen och dämde upp Nasaissjön. Ovannämnda terrass i Svaipa på 1 010 m hör också dit. Liksom i andra fjälldalar avlöstes Nasaissjön av andra issjöar med allt lägre nivåer och allt ostligare läge. Den yngsta issjö, jag sett spår av ovanför Storlaisan, omfattade de tre övre sjöarna, med vattenyta 472 m ö. h., d. v. s. 20 m över Gautojaur och med avlopp N om nuvarande. — Den dalen successivt genomdragande istungan saknar icke intresse för tolkningen av SE-erosionens större belopp i dalen än på bergen.

Från och med Storlaisan luta spåren av isens övre yta åt motsatt håll. I fjället Nebsuort (kartan siffran 914) finnas upp till nära under toppen på dennas SW-sida skvalrännor och terrasser från detta fjälls begynnande nunatakkstadium, vilka ha en svag men bestämd lutning åt SE, trots de ingående moränblockens ostliga karaktär. Isdelaren torde alltså redan då ha innehaft sitt slutläge vid Storlaisans västända. Under liknande förhållanden framsmälte Björnberget, 622 m, på sjöns ostsida.

Sedan isytan sjunkit 500 m från nunatakkstadiet på Nebsuort, och iskanten förflyttat sig till sjöns norra tredjedel, var den obetydliga isresten — kanske ännu 100 m mäktig — förmögen av en framstöt såsom framgår av ett tungbäcken med ändmoräner av sjöbottnens bergarter snett uppskjutna på den av täckbergarter uppbyggda stranden (vid Skårro, lokal 56).

Då en klimatförsämring ingalunda kunnat ge denna isrest någon tillväxt (yngre refflor fr. NW saknas ju f. ö. ovanför Storlaisan) eller ökad rörlighet, tillskriver jag den nya aktiviteten trycket från den uppdämda vattenmassan, för vilket den reducerade ismassan långsamt reagerade. Då is icke nybildas vid issjön, måste en issjöjökels historia bli kort. Desto mera anmärkningsvärd är den påtagliga erosionen. En sådan utmärkte också de av Caldenius (1942) beskrivna framstötarna i Halland, vilka, mot bakgrunden av Nilssons (1942) vid samma möte påvisade issjöar, möjligen kunna ges en liknande tolkning, beroende på graden av samtidighet. Issjön verkade där efter en bredare front men på grund av det större vattendjupet starkast i dalarna. Ahlmann framhöll vatteninfiltrationens betydelse för isens rörlighet.

### Isströmningen enligt blocken.

Hällskulpturen kompletteras av blocktransporterna. Hällstudierna ge ensamt den precisa upplysningen om isdelarens sista läge samt de olika vandringarnas historia. Men de skulpturer, som skulle visa isdelarens yttersta lägen i öster och väster, måste, åtminstone i stor utsträckning, ha utplånats av de senare ismassor, som i riktning från isdelarområdet med utåt ökat erosionsbelopp överströmmat nämnda äldre ytterlägen. Även blocktransporterna ge oss minimimått, men med gynnsamt belägna klyftorter för ledblock ökas möjligheterna. I förevarande fall ha blockstudierna väsentligt utvidgat den genom skulpturen hittills kända amplituden såväl åt väster som åt öster och dessutom visat, att även öströmmen, vars spår varit svåra att upptäcka på höjderna, fört ostliga block upp på de högsta fjällen.

Det var för mig helt överraskande att i Nasafjäll finna en massformig granit och för undersökningen värdefullt, att denna visade sig såväl med hänsyn till den säregna petrografiska karaktären som till förekomstens begränsning vara förstklassig som ledblock. Det är en helt annan typ än låglandets röda graniter. Den i Nasafjäll på svenskt område anstående, mest grova men ibland finkorniga bergarten är en ljus biotitgranit, vars biotitpartier ej utgöras av enhetliga korn utan av en fin gyttring. Mikroskopiskt visar den sig enligt hemförda stuffer titanitrik med något primär epidot. Zenzén har närmare beskrivit den (1927 s. 362). I någon del av Nasafjäll måste graniten dock vara hornbländeförande, emedan Törnebohm (1878 s. 169) karakteriserar den som sådan. Enligt Rekstad (1913 s. 29) och efter honom Holmsen (1932 s. 44) är detta fallet på norsk sida. »Fra Gubbeltåga (första dalgång W om Nasa) henover mot Nasa fører den i stor udstrekning hornblende.» W och NW om Gubbeltåga uppträda enligt Oxaal (1919 s. 28, 29) andra typer. Enligt Vogt (1900 s. 143) är Nasagraniten i allmänhet starkt pressad.

Om den massformiga granitens utbredning gäller, att den i Nasafjälls södra och östra sluttning knappast når ner till bergets fot men åt NE enligt Svenonius pl. 18 kilformigt avsmalnande följer riksgränsen ett stycke upp på Svangsfjället. Alla omgivande berg äro uppbyggda av »gnejs, granulitskiffer» (starkt resp. mycket starkt pressad fjällgranit, sannolikt av nasamagman, flackt växellagrande med tunnare led av äldre skiffrig berggrund). En massformig granit (av nasabergartens utseende) anstår enligt Svenonius på svensk sida först i Garremtjåkko vid Graddis, med sydgräns 7′ N om vårt kartområde och ostgräns 15° 58′ Ö. L. (jfr Holmquist 1900 s. 91, 243 och tavla 3). En av Svenonius i Laisdalen med granittecken utmärkt liten förekomst har jag besökt och funnit bestå av pressad fjällgranit.

Ovannämnda, från Nasafjäll nämnda bergartstyper äro vanliga såsom block i Laisdalen med dess bidalar (lokalerna a på kartan).

Som exempel på ostliga och västliga block i högt läge väljer jag Svaipa, som är högsta fjäll på Laisdalens sydsida (1 426 m). Uppe på Svaipas vida topp-platå iakttogos i förbigående många block av ostligt ursprung, inte bara av låglandets graniter (7 block) och täckande syeniter (5) utan jämväl av Laisvalls sandstensserie (7), särskilt det gröna arkoskonglomeratet (5) samt som västliga block en eller annan fjällgranit. I detta starkt lavklädda blockhav av huvudsakligen fjällets egen kvartsit förbigår man lätt ev. block av Nasafjällets vita granit. Jag har därför gjort en studie bland de rennötta block, som uppbygga den milsvitt synliga jättelika lavinkäglan i en bäckränna från Svaipa och Ertektjåkko, 25—100 m över Laisans yta (a på kartan). I denna lavinkägla, som sålunda härstammar från Svaipa- och Ertekfjällens platåhöjder och sammansättes av material från såväl dessas egen frostsprängda berggrund som deras morän, gjorde jag en räkning av alla under en och samma tid påträffade block av eruptivbergarter och arkoser. Listan är följande: 8 nasagranit, 22 låglandsgranit, 8 grönt arkoskonglomerat, 31 syenit- och granitmylonit från Laisvalls undre överskjutningsskålla, 6 amfibolit av typ, som anstår på 1 393 m i Svaipas ostsida, 1 dito av typ funnen i lavinkägla på Svaipas SE-sida. Nasagraniten är representerad av 5 block identiska med proverna av den epidotförande biotitgraniten i Nasafjäll, 2 äro pressade led av densamma och 1 är hornbländeförande.

Vid mitt föredrag i Uppsala den $^{25}/_{2}$ 1943 upplyste professor Backlund, att han på återväg från Nasafjäll till Vindelälvens dalgång påträffat ett block av Nasagranit SE om Nasafjäll, se kartan. Detta meddelande tillmäter jag stort värde. Blockets höjdläge i övre sluttningen av Kargasetåive visar, att det icke har transporterats dit av en dalglaciär utan av en is tillräckligt mäktig och oberoende av orografien för att övertvära Silbojaurs dalgång.

Professor Backlund har senare också haft vänligheten uppgiva 2 à 3 förekomster (b) av en bergart, av vilken jag längre ner vid Laisälven påträffat en smal men meterlång sexsidig pelare, morfologiskt påminnande om en ytlava men mikroskopiskt av närmast kvartsitisk sammansättning. Den verkliga klyftorten torde finnas inom samma zon, kanske längre åt NE.

Under mina blockräkningar vid Storlaisan kände jag icke Nasagraniten. Men flera block har jag där provtagit, som jag nu kunnat identifiera med den pressade fjällgraniten i Laisdalens översta del (c). Och block av Svaipas fjällkvartsit (d) äro mycket vanliga på stränderna av Storlaisan och bergen däromkring.

### Sammanfattning.

Av hällskulpturen och blockrörelserna längs Laisdalen har samstämmigt framgått, att isdelaren vid nedisningens början haft sitt läge långt västerut i fjällen, åtminstone vid vattendelaren och troligen ett stycke väster därom, på norskt område. Därefter har den förflyttats åt öster, minst så långt som ett stycke in på granitterrängen vid fjällranden. Här saknas ännu undersökningar. Men då isdelaren ännu under 3:e fas, som betecknar ett stillestånd under ett framskridet stadium av avsmältning (ra-tid?), enligt lokal 46 vid Hornavan ännu låg på granitterrängen, bör den under den maximala utbredningen ha legat betydligt östligare.

Från sitt östliga läge drar sig isdelaren under den fortsatta allmänna avsmältningen åter in i fjällen, inom vårt kartområde till omkring 16° 45′ Ö. L.

Hällskulpturen har visat, att isdelarens första västliga läge — även om icke hela tiden det allra västligaste — haft en mycket stor varaktighet jämfört med det ostliga läget. Därmed överensstämmer också, att strömmen från SE, vars rikliga leverans av granitblock till fjällområdet får ställas i samband med det överskridna granitbältets bredd, lämnat kvar vid fjällranden en riklig förekomst av fjällblock, som transporterats ned av den första strömmen från NW. Särskilt vill jag framhäva blocken av den vita fjällkvartsiten, som anstår endast i ett relativt smalt bälte tvärs över dalgången och så västligt, att det enligt hällskulpturen omöjligen kan ha passerats eller ens nåtts av isdelaren under dess återvandring motfjälls.

Därav måste följa, att isens stora låglandsöversvämning med utbredning på kontinenten utgjort en förhållandevis liten del av den sista nedisningen. Innebörden däri, liksom också frågan om hur pass representativ den undersökta profilen kan anses vara, skall upptagas i annat sammanhang (1943 b).

Isdelarzonen, vars refflor tidigare närmast givit bilden av ett virrvarr av rörelser hit och dit, visar sig vid systematisk hällanalys vara ett innehållsrikt dokument för kunskapen om särskilt de betydande delar av vår istid, som icke varit åtkomliga för hittills tillämpade geokronologiska metoder. Detta kan sägas med så mycket större skäl, som isdelarområdet synes väl avspegla även avsmältningstidens samtidiga processer vid och utanför isranden, vilkas tidsföljd är väl känd genom den svenska geokronologien.

## Zusammenfassung. Eisscheidenstudien am nördlichen Polarkreis.

Man hat immer angenommen, dass eine Felsskulptur in der Form von Rundhöckern und Schrammen aus den früheren Stadien der letzten Vereisung Skandinaviens unmöglich erhalten sein könne (Enquist 1918 S. 23), ja nicht einmal aus der Zeit der maximalen Vereisung (Sjögren 1909 S. 111). Verf. hat ein Profil durch die bottnische Abdachung des Kölen untersucht und fast dem ganzen Profil entlang eine glaziale Felsskulptur aus der Zeit vor der extramontanen Verlegung der Eisscheide nachgewiesen. Da diese frühe, einer westlich intramontanen Eisscheidenlage entsprechende Skulptur die glazialen Formen der Höhen mehr beeinflusst hat als diejenige der extramontanen Eisscheidenlage, welche zeitlich der Flachlandvereisung entspricht, so folgt daraus, dass die Flachlandvereisung nur einen verhältnismässig späten Teil der letzten skandinavischen Vereisung auszeichnet. Das wird Konsequenzen für die Deutung der Randseen haben und einen Vergleich mit der quartären Vereisung Patagoniens ermöglichen, wo Verf. früher eine westliche Eisscheidenlage nachgewiesen hat.

## Anförd litteratur.

Ahlmann, H. W:son; Laurell, Erik; och Mannerfelt, Carl (1942): Det norrländska landskapet, särskilt dess topografiska och kvartärgeologiska utveckling. Ymer.

Caldenius, C. C:zon (1909): Några iakttagelser angående isdelaren i Jämtland. G. F. F. Bd 31.

— (1942): Gotiglaciala israndsstudier och jökelbäddar i Halland. G. F. F. Bd 64.

De Geer, G. (1888): Om isdelarens läge under Skandinaviens bägge nedisningar. G. F F. Bd 10.

Durocher, J. (1846): Études sur les phénomènes erratiques de la Scandinavie. Bull. Soc. Géolog. de France. 2:me sér. IV. Paris.

Enquist, Fredrik (1916): Der Einfluss des Windes auf die Verteilung der Gletscher. Bull. Geol. Inst. Upsala Vol. XIV.

— (1918): Die glaziale Entwicklungsgeschichte Nordwestskandinaviens. S. G. U. Årsbok 12. Nr 285.

Fredholm, K. A. (1891, 1892): De glaciala företeelserna i Norrbotten. G. F. F. Bd XIII, XIV. Jfr Sv. Geol. Unders. Ser. C. Nr 117, 1892.

Frödin, G. (1925): Studien über die Eisscheide in Zentralskandinavien. Bull. Geol. Inst. Upsala Vol. XIX.

Frödin, J. (1914): Geografiska studier i St. Lule Älvs källområde. S. G. U. Ser. C. Nr 257. Årsbok 1913.

Gavelin, A. (1906): Några iakttagelser rörande istidens sista skede i trakten NW om Kvikkjokk. G. F. F. Bd 28.

— (1909): Diskussionsinlägg efter Hambergs föredrag. G. F. F. Bd 31.

— (1910): De isdämda sjöarne i Lappland och nordligaste Jämtland. S. G. U. Ser. Ca Nr 7.

Geijer, P. (1922): Block av Sevebergarter vid Kiruna. G. F. F. Bd 44.

Granlund, Erik (1936): De kvartära bildningarne. I Magnusson-Granlund, Sveriges geologi.

Hamberg, A. (1909): Om inlandsisens avsmältning i fjälltrakten mellan Stora och Lilla Lule Älf. G. F. F. Bd 31.

Holmquist, P. J. (1900): En geologisk profil öfver fjellområdena mellan Kvikkjokk och norska kusten. G. F. F. Bd XXII.

Holmsen, G. (1932): Rana, beskrivelse till det geologiske generalkart. N. G. U. nr. 136.

Högbom, A. (1937): Skelleftefältet. S. G. U. Ser. C Nr 389.

Högbom, A. G. (1885): Glaciala och petrografiska iakttagelser i Jämtlands län. S. G. U. Ser. C. Nr 70.

Hörbye, J. C. (1857): Observations sur les phénomènes d'érosion en Norvège. Christiania.

Kautsky, Fritz (1940): Das Fenster von Gautojaure im Kirchspiel Arjeplog, Lappland. G. F. F. Bd 62.

Ljungner, Erik (1930): Spaltentektonik und Morphologie der schwedischen Skagerrak-Küste III: 1. Bull. Geol. Inst. Upsala Vol. XXI.

— (1943 a): Dito III: 2 (under tryckning).

— (1943 b): East-west-balance of the Quaternary ice cap in Patagonia and Scandinavia. Bull. Geol. Inst. Upsala Vol. XXX (under tryckning).

Lundqvist, G. (1935): Isavsmältningen inom Bergslagen. G. F. F. Bd 57.

— (1942): Jordarterna och deras fördelning inom Norrland och Dalarne. Ymer.

Nilsson, Erik (1942): Gotiglaciala issjöar i södra Sverige. G. F. F. Bd 64.

Oxaal, J. (1919): Dunderlandsdalen. N. G. U. nr. 67.

Rekstad, J. (1913): Fjeldstrøket mellem Saltdalen og Dunderlandsdalen. N. G. U. nr 67.

— (1917: Fjeldstrøket Fauske-Junkerdalen. N. G. U. nr 81: 4.

Sahlström, K. E. (1914): Glacial skulptur i Stockholms yttre skärgård. S. G. U. nr 258.

Sauramo, Matti (1931) i Ramsay, Geologiens grunder II s. 385. Helsingfors.

Sjögren, Otto (1909): Geografiska och glacialgeologiska studier vid Torne Träsk. S. G. U. Ser. C. Nr 219.

Svenonius, Fredrik (1895): Nasafjälls zink- och silfvergrufvor. G. F. F. Bd 17.

Tanner, V. (1915): Studier öfver kvartärsystemet i Fennoskandias nordligare delar. III. Bull. comm. géol. Finl. Nr 38. Helsingfors.

Törnebohm, A. E. (1872): Några iakttagelser med afseende på flyttblocken i Jämtland. G. F. F. Bd 1.

— (1878): Om bergbyggnaden inom de sydligare svenska lappmarkerna. G. F. F. Bd IV.

Zenzén, N. (1927): De geologiska förhållandena vid Nasafjälls gruvfält. G. F. F. Bd 49

# Notis.

## Diabasgångar och gångdalar i trakten av Tisaren.

Av

ARVID BERGDAHL.

Under morfologiska rekognosceringar i Tisarens omgivningar i Närke sommaren 1941 råkade jag på en diabasgång, som väckte min uppmärksamhet, dels emedan den trots sin bredd och uthållighet ej var känd av geol. kartbladet (Breven), dels emedan den i oväntad grad visade sig vara bestämmande för de topografiska dragen längs densamma. Fyndet blev anledning till blockstudier även i omgivningarna såväl S som V om Tisaren, varunder ytterligare fyra gångar blevo funna. Dessutom har en stark frekvens av stora diabasblock observerats på ännu en lokal, där emellertid moderklyften icke hunnit bli avslöjad.

*Dovragången.* Nyköpingsåns källsjö, Tisaren, har endast obetydliga tillflöden. Det viktigaste kommer från V och upprinner i en markerad sprickdal, Dovradalen, som i ung. nordlig riktning genomskär ensliga skogstrakter på gränsen mellan de tre socknarna Lerbäck, Viby och Snavlunda. Dalen, som i N går ända fram till hallsbergslinjens förkastningsbrant och är ung. en halv mil lång, hyser tre långsträckta sjöar, Norra, Mellersta och Södra Dovrasjön samt längst i S den lilla Lersjön. Till sin allmänna habitus avviker den knappast från en mängd andra dalar, som i samma huvudriktning genomsätta tisarebäckenet och dess omgivningar, även om den är mera utpräglad och uthållig än flertalet andra.

VNV om gårdarna vid Dovra går en kort tvärdal åt V ända fram till Dovrasjöarnas avlopp, genom vilken man bekvämt kommer in i Dovradalen, som särskilt N härom begränsas av höga bergstup på båda sidor ända fram till nämnda förkastningslinje. Följer man nu dalen åt N, står man snart framför en jämn åsrygg, som höjer sig från dalens botten (Fig. 1). Vegetationen på åsen röjer en näringsrik jordmån, vilken också tidigare lockat till odling, och stenrösen följa dalen ett par hundra meter. Blocken i dessa visade sig nästan undantagslöst bestå av diabas.

Efter sådana rika blockfynd var det ej svårt att finna den fasta klyften, om än lokalerna mestadels lågo dolda av växttäcket. Det är en blågrå medelgrov olivindiabas med omkring 2.5 mm långa plagioklastavlor. Blocken äro vanliga ända fram till sydändan av S. Dovrasjön, där gången tydligen fortsätter ut på bottnen. Längre åt N ha blockmaterial och berggrund icke närmare undersökts, varför det ännu är en öppen fråga, om diabas- och dalgång även i fortsättningen följas åt.

Diabasgången har ryggform endast en kort sträcka, varefter den åt N småningom övergår i en terrass längs den östra bergväggen, medan bäcken i sin nedskurna fåra följer den västra. Genom slingrande rörelser åt motsatt

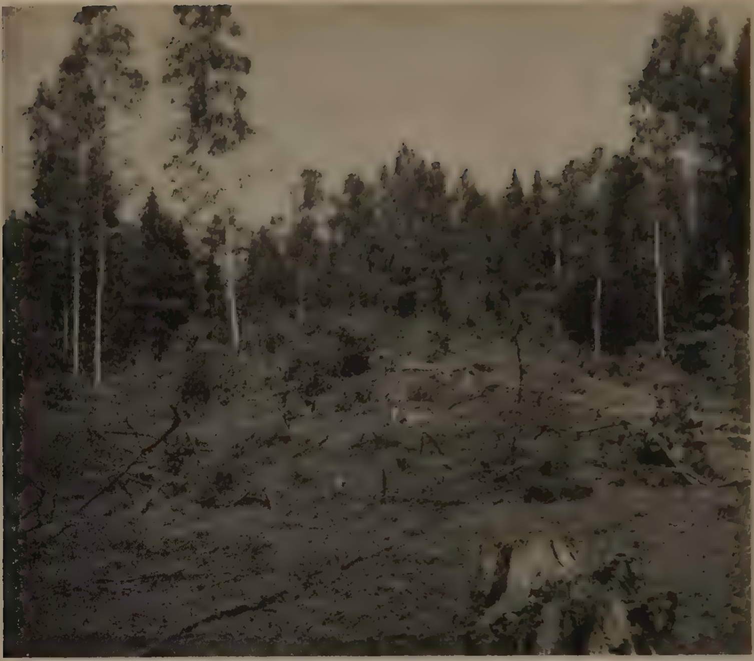


Fig. 1. Diabasgången i Dovradalen.

håll byta sedan terrass och bäckdal plats två ganger, varigenom den sistnämnda alltså lika många gånger översneddar diabasgången.

Vid övergången mellan dalbottnens ås- och terrassformiga del uppmättes en tvärprofil. Dalens bredd var 55 och största djup 18—19 m. Upptager diabasgången hela dalens bredd, eller hur stor är dess mäktighet? Där profilen skär bäcken, som här rinner längs västsidan av dalen, är denna nederoderad i gnejsen, men endast ett par m O därom eller omkring 5 m O om bergbranten sticker diabasen upp vid terrassens bas. En liknande iakttagelse gjordes 125 m S om S. Dovrasjön. De yttre agentierna, framför allt exarationen, ha alltså ej arbetat endast på djupet utan även breddat dalen, vilket gynnats av en stark förklyftning i gnejsen längs salbandet. Här har också djuperosionen kunnat sätta in med största effekt. Vid östra bergväggen märktes ingen klyftzon, men berggrunden var dold på dalbottnen intill. Man behöver emellertid ej förutsätta, att den tektoniska spänningen utlösts utefter mer än ett rörelseplan i den trånga dalen, det som angives av bäckens läge. Likväl har även här erosionen åstadkommit någon breddning att döma av bergväggens utseende och saknaden av diabasrester. Gångens mäktighet kan därför uppskattas till omkring 40 m.

*Fisklösengången.* En skärning vid vägen SO om den lilla sjön Fisklösen (SO N. Nyckelhult i Lerbäcks socken, Fig. 2) lockade till granskning, emedan den hyste rikligt med knytnävstora rundade block, koncentriskt skålvittrade på för diabaser känt sätt. Moränen, som även innehöll större kantiga dia-

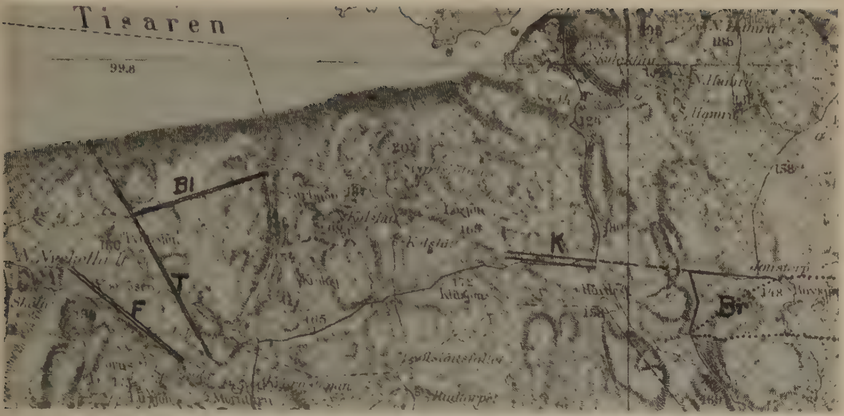


Fig. 2. Klipp ur konceptbl. Sävstaholm SV med inlagda diabasgångar. F = Fisklösengången, T = Tvättsjögangen, Bl = Blomsterhultsgangen, K = Kolslättsgången, Br = Brevengången. ············ — Brevengångens gränser enligt geol. kartan. Skala 1 : 67 000-

basblock, gav intryck av lokalmorän, varför fast klyft ej kunde vara långt borta. Den anträffades också några tiotal m NV och NO om grustaget. En annan lokal med kontraktionssprickor angav gångens ungefärliga riktning, och denna kunde sedan med hjälp av en rad andra blottningar, även kontaktfynd, preciseras till N 50° V. Bland inneslutningarna märktes en två m tjock gnejslins, som brant och tvärt höjde sig 2—3 dm över den omgivande diabasen, framvittrad ur denna. Kontaktlinjen sneddade här ej rakt över gnejsens ostvästliga strykning utan gick i sicksack, omväxlande följande strykningen och normalen till denna.

Diabasgången pekar åt NV mot Fisklösen, vars botten den torde bilda. Spår av en kontakt är funnet vid norra stranden. Rekognosceringen fortsattes åt SO, där en skarpare utskuren dal med göl och kärrmarker tog vid. Bergbranten längs dess SV-sida visade inga diabasrester och ej heller någon klyftzon, medan däremot den motsatta dalsidan hade en intressant kontaktyta blottad. Denna är ung. 100 m lång, 3—4 m hög och hänger något över åt SV med en stupning av 70°, N 40° O. Dalen blir djupare åt SO, men bergväggen övergår där snart i en rasbrant. Den överhängande bergväggen är i stor utsträckning klädd med finkorniga diabaslameller av några få cm tjocklek. Här har magman trängt in i sidostenen på klyftfogar, parallella med huvudgången. Rasbranten börjar just, där en från N kommande klyftfraktur genomskär bergväggen och åstadkommer ett belysande tvärsnitt (Fig. 3). SO om detta ligga högre laterala partier av gången delvis kvar, skyddade av den överhängande gnejsväggen.

Den genom diabasens bortskaffande uppkomna dalgången fortsätter rakt åt S 50° O, tills den utmynnar i myrmarkerna vid Mörntärn. Eruptivgångens mäktighet torde snarare över- än understiga 30 m.

*Trättsjögången.* Från Mörntärnsmyren utstråla mot Tisaren tre sprickdalar (Fig. 2): Gropdalen, i vilken en gren av Kroksjön ligger, Fisklösendalen, som nyss omtalats, samt mellan dessa ett mindre dalstråk i N 25° V, som inmynnar i Mörntärnsmyren 200 m O om Fisklösendalens mynning. Det nämnda dal-

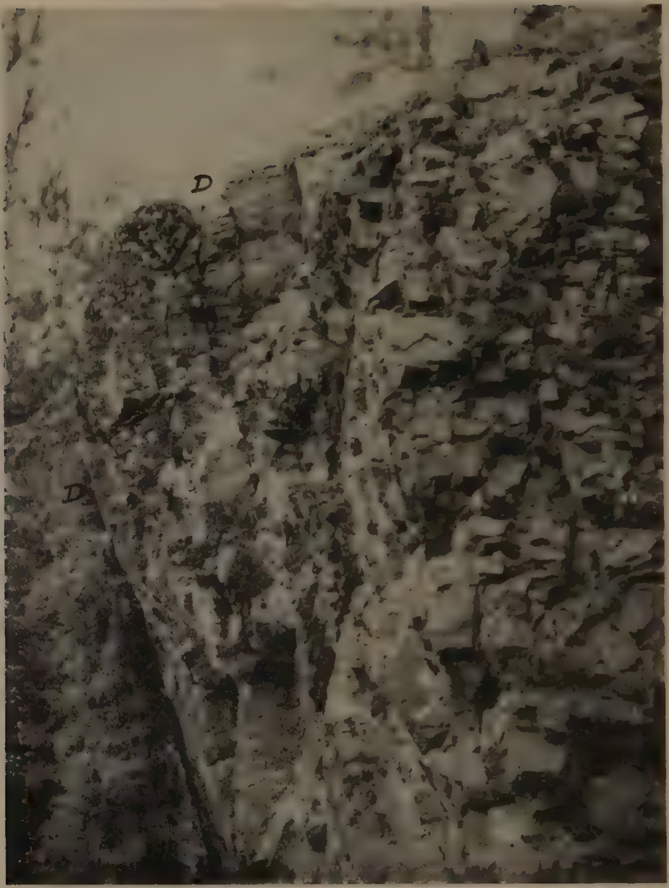


Fig. 3. Tvärsnitt genom dalens NO-vägg vid Fisklösengölen samt en klyftzon, som följer dalen. D = smala diabasgångar.

stråket har uppkommit på samma sätt som de förut beskrivna. Redan 40 m från myrkanten är diabasen frameroderad i en bäck. I denna dal är det påtagligt, att den kraftigaste upprensningen i huvudsak skett utefter gångens SV-flank. Dalbredden varierar, mest beroende på hur stor del av gångens bredd, som nedbrutits och bortförts. Belysande är lokalen 150 m N u i Karlslund (konceptbl.), där dalen har en bredd av 15 m mellan de brant uppstigande bergväggarna: gnejsen i SV, diabas i NO. Här kvarligger nämligen till jämnhöjd med dalens omgivningar en 17 m mäktig diabaspacke, blottad till närheten av NO-kontakten, och därmed skulle hela gångbredden bli högst 32 m. Strax intill smalnar den grunda dalen till endast 6 m.

Utmed dalens NO-sida äro brant stupande diabasväggar vanliga och falla i ögonen genom sina släta och plana ytor. Tydligen har upprensningen ägt rum utefter de längsgående kontraktionssprickornas branta plan, som stupa

75—80° mot ONO, varigenom bergväggen även här blivit något överhängande. Dylika sprickor ha observerats på flera ställen, där de uppdelat bergarten i parallellepipediska block, vars stående långsidor gå parallellt med dalen, medan de båda övriga planen ligga ung. vinkelrätt däremot. Vittring och erosion ha här kunnat arbeta med större framgång än utanför diabasgången och desto snabbare ju bättre kontraktionssprickorna kommit till utbildning. Dessa gångar ha tydligen utgjort svaghetsbälten i berggrunden och detta ej enbart genom förekomsten av kontraktionsytor utan ännu mer därigenom, att utefter gångarna den tektoniska spänningen utlösts under bildning av förklyftade rörelseplan, ofta längs ettdera salbandet, och dessa ha givetvis i första hand varit vägledande för de exogena krafterna.

Där gången skär vägen (600 m SO t i N. Nyckelhult), är ena kontakten väl exponerad, visande strykningen N 25° V. Dess bredd är 25 m. Hittills har gången varit dalbildande, även om sänkan bitvis varit smal och grund, men i fortsättningen åt NV är till en början denna egenskap ej framträdande. Nu genomsätter den sydvästsluttningen av en höjd, där ena kontakten kan lokaliseras på metern. N Tvättsjömyren följes gången åter längs sydvästra sidan av en liten smal men väl markerad dalsträckning, i NO ofta begränsad av diabasens plana bergvägg. På förkastningsbranten mot Tisaren synes gången ligga helt dold under moränen. Endast lösa block ha anträffats, däribland ett meterstort nära sjöns strand.

*Blomsterhultsgången* löper i huvudsak längs stigen N. Nyckelhult—Svartsjön och har riktningen N 70—80 O med svagt slingrande eller sicksackformigt lopp. Den är följd endast mellan Tvättsjögången i V och Gropdalen i O och är under denna sträcka högst 18 m bred. Stupningen har icke varit åtkomlig för mätning, då gången ej är dalbildande. Smärre bergrännor från N i isrörelseriktningen övertvära diabasen utan att ta något intryck av denna. Gången är av intresse, dels emedan den stryker ung. parallellt med den stora tisareförkastningen, dels emedan den i O når fram till en av de mest utpräglade sprickdalarna S om Tisaren, Gropdalen (Gropedal). Den har kunnat följas under vegetationen ända fram till dalens västra brant men kunde vid en hastig granskning av den motsatta dalsluttningen ej återfinnas. Om detta beror på att den förenar sig med en annan gång i Gropdalen eller att en förskjutning ägt rum mellan blocken längs denna sprickzon eller att den slutar blint är alltså ännu oavgjort.

*Kolslättsgången.* Upptäckten av nämnda diabasgångar förde givetvis tankarna till Brevengången, vars västra ände på bladet Breven ligger 16 km från Dovragången men endast 4 km från Mörntärn och Gropedal. Då direkt konnektering ansågs möjlig men den disponibla tiden var kort, gjordes två dagars försök att finna den felande länken närmast Brevengången genom att inventera grustag och skärningar längs vägarna. Ett lovande uppslag gavs 1 km O om gården Kolslätt, där vägen grävts genom en i nordlig riktning utsträckt moränbank, innehållande rikligt med diabasblock. 50 m N om vägen, som här följer en ostvästlig dalsänka, var den på bottenvegetation fattiga sluttningen belamrad med fritt liggande block, mest av diabas, längs en 100 m lång ostvästlig front. I isrörelseriktningen åt N stäcktes snart förhoppningarna att finna moderklyften av en tvärande gnejsrygg. Spaningsradien måste svängas upprepade gånger ända till västlig riktning, och slutligen lyckades jag finna en låg, nästan övervuxen berghäll, till större delen bestående av diabas, där det var möjligt att på metern fixera gångens norra gräns. Då ledblocken ett par hundra meter åt O lågo alldeles inpå den i N uppstickande gnejsryggen, kunde riktningen rätt väl preciseras till N 75 à 80° V. Mäktigheten torde uppgå till minst ett 50-tal m. Gångens södra flank ligger i bottnen av den diffust utbildade dalen.

Diabasgången följdes nu at O, och dä riktningen var känd, vållade detta ingen svårighet. Längs vägen till Hävde vägskäl, först på norra sedan pa södra sidan, anträffades den på flera ställen, tills den vid vägskälet dök ner under en myr. Dess uppspårande på andra sidan denna såg ut att kräva för lång tid. Kanske var det lättare att konnektera från O, fran Brevengångens västra ände.

Brevengången visade sig här vara ganska bristfälligt karterad på geol. kartbl. På detta svänger gångens nordgräns fran Rävsjön i sydvästlig riktning, vilket ej är fallet. I verkligheten går den från sjöns norra strand nästan rakt åt V (N 85° V) fram till Lövsjöarnas avlopp (Lövsjödalen) följande skogsvägen. Denna gör vid bäcken en skarp krök åt SSO och inramar tillsammans med geol. bladets diabasgräns en liksidig triangel med 500 m sida, vars berghällar karterats som gnejs. Alla dessa jämte övriga inom området ej tidigare observerade utgöras av diabas. Ännu vid Lövsjödalen är alltså Brevengången alltfort 500 m bred. Härigenom kommer dess nordgräns att stryka rakt mot Kolslättsgången.

Så långt var allt gott och väl. När det sedan gällde att finna diabasens fortsättning V om dalen, blevo försöken fruktlösa, möjligen beroende på den ofullständiga rekognosceringen. Möjligen kunna vissa iakttagelser, bl. a. rörande den kalcitbreccierade diabasmantel, som bekläder Brevengångens västände, ge stöd för den uppfattningen, att en event. fortsättning åt V av en eller annan gren från huvudgången förflyttats genom förskjutning av den mellan Lövsjö- och Håvdedalen liggande bergribban.

Föreliggande fragmentariska framställning är — frånsett den ofullständiga gångkarteringen — avsedd att framhäva det för området viktiga spörsmålet dalgång—gångdal. Givetvis kräves omfattande systematisk rekognoscering, innan ens de viktigare diabasgångarnas förekomst och sträckning hunnit bli utredda, men först därigenom blir det möjligt att bedöma den betydelse, som gångarna kunna ha haft för de aktuella sprickdalarnas anläggning i trakten. Sannolikt dölja sig i dessa isolerade delar av det gamla Tylöskog åtskilliga gångar under skogarnas täta växttäcken och dalarnas kärriga och sjörika bottnar, men de torde ofta vara omöjliga att avslöja.

## Mötet den 4 mars 1943.

Närvarande 39 personer.

Ordföranden, hr Helmer Hedström, meddelade, att styrelsen till nya ledamöter av Föreningen invalt bergsingenjören Carl-Ingemar Sahlin, Malmberget, föreslagen av hrr Geijer och Zenzén, och e. adjunkten fil. mag. Esbjörn Carlson, Borås, föreslagen av hrr Troedsson och Sahlström.

Professor G. Aminoff hade på sin 60-års dag den 8 februari uppvaktats genom styrelsen. Med anledning härav hade en tacksamhetsskrivelse inkommit från hr Aminoff.

Med Geografiska Förbundet hade träffats överenskommelse om gemensamt sammanträde den 10 mars 1943.

Revisionsberättelse över styrelsens och skattmästarens förvaltning under år 1942 föredrogs, varefter av revisorerna tillstyrkt ansvarsfrihet beviljades.

Sammandrag av Geologiska föreningens räkenskaper för år 1942.

### Debet.

| | | | |
|---|---|---|---|
| Balans från 1941: Reservfondens konto | kr. | 10,731: 63 | |
| Lotterifondens konto | » | 10,000: — | 20,731: 63 |

Inkomster under år 1942.

| | | | |
|---|---|---|---|
| Reservfondens konto, räntemedel | kr. | 322: 21 | |
| Lotterifondens » » | » | 490: 39 | |
| Annonser | » | 376: 56 | |
| Trycknings- och korrigeringsbidrag | » | 2,797: — | |
| Försäljning av föreningens förhandlingar | » | 479: 75 | |
| Statsbidrag | » | 1,600: — | |
| Bidrag av Jernkontoret | » | 1,000: — | |
| Portoersättningar | » | 42: — | |
| Årliga ledamotsavgifter | » | 3,953: 50 | |
| Ständiga ledamotsavgifter | » | 500: — | 11,561: 41 |

Utgående balans:

| | | | |
|---|---|---|---|
| Skuld till P. A. Norstedt för tryckning | kr. | 2,088: 20 | 2,088: 20 |
| | | Summa kronor | 34,381: 24 |

### Kredit.

Utgifter under år 1942.

| | | | |
|---|---|---|---|
| G. F. F. 1941, rest å tryckning | | kr. 1,477: 15 | |
| » 1942, tryckning betald | kr. 7,329: 55 | | |
| » » , » ogulden | » 2,088: 20 | | |
| » » , klichéer | » 1,392: 05 | | |
| » » , referat | » 96: 90 | | |
| » » , revue annuelle | » 301: 50 | | |
| » » , distribution | » 362: 59 | » 11,570: 79 | |
| Expeditionskostnader | | » 366: 87 | |
| Sammanträden | | » 257: 85 | |
| Diverse | | » 126: 95 | |
| Arvoden | | » 1,350: — | 15,149: 61 |
| Utgående balans: | | | |
| Reserfondens konto | | kr. 11,231: 63 | |
| Lotterifondens » | | » 8,000: — | 19,231: 63 |
| | | Summa kronor | 34,381: 24 |

Föreningen beslöt ingå med ansökningar dels till Kungl. Maj:t om ett statsbidrag å 1,600 kronor, dels till hrr fullmäktige i Jernkontoret om ett anslag av 1,000 kronor såsom bidrag till fortsatt utgivande av Förhandlingarna under år 1943.

Hr Ljungner höll ett av talrika ljusbilder belyst föredrag om Isdelarstudier vid polcirkeln. En uppsats i ämnet är intagen i detta häfte av Förhandlingarna.

Med anledning av föredraget yttrade sig hrr A. Gavelin, Geijer, De Geer och lic. C. Mannerfelt samt föredraganden.

Hr A. Gavelin uttryckte sin tillfredsställelse över att föredraganden upptagit detaljundersökningar inom dessa tidigare endast översiktligt studerade trakter och han hade med stort intresse följt redogörelsen för de förut föga beaktade glacialmorfologiska detaljer som föredraganden skickligt framletat.

Beträffande isdelaren och dess förflyttningar hade man vid de tidigare undersökningarna, särskilt talarens, måst lägga huvudvikten på studiet av blocktransporterna, alldenstund dessa lättast kunde ge besked om huru långt österut som isdelaren under den sista landisens slutskede åtminstone måste hava nått. Att den under ännu äldre skeden av den sista nedisningen troligen måste ha legat vida längre österut kunde då postuleras men icke direkt bevisas. De på talarens, liksom andras, äldre kartor angivna isdelarläget betecknade alltså minimiläget mot öster under ett visst icke närmare fixerat men dock ganska tidigt skede av landisregressionen (och innan ännu fjällen i någon större utsträckning blottlagts). Att isdelaren med avsmältningens fortskridande sedermera förflyttades allt mera mot fjällen i nordväst framgick ju också av många förhållanden inom de olika floddalarna. För Lilla Lule älv hade tal. kommit till den uppfattningen, att den sista isdelaren måste hava ryckt tillbaka ända till vattendelaren mellan Lilla och Stora Lule älvar, c:a 6 mil NW om Kvikkjokk.

Av stort intresse vore enl. talarens mening att få konstaterat huru långt österut som landisen nått sedan isdelaren åter förflyttats till högfjällsområdena. Särskilt Lilla Lule älvs dalgång torde lämpa sig för sådana studier. Efter denna dalgång funne man nämligen en mängd fjällbergarter, däribland särskilt de utomordentligt karakteristiska bergarterna från Ruoutevare-området, påfallande rikligt i morän och rullstensgrus ända så långt ned som talaren haft tillfälle göra iakttagelser däröver, d. v. s. åtminstone ned till Murjektrakten. Det vore av intresse att utröna, om det finnes någon markerad nedre (östlig) gräns för denna blocktransport från fjällen.

I detta samband ville talaren också framhålla, att han ofta frapperats av den icke ringa frekvens av röda sparagmitsandstenar och kvartsiter från de östligare fjällområdena, vilka förekomma ända ned i Umeå-trakten och i Ångermanlands kustområden.

Av särskilt intresse vore det av föredraganden berörda problemet om de moräntäckta sedimenten, först beskrivna från Östersundstrakten men nu kända från så många lokaler inom ett visst N—S:ligt bälte, att de måste sättas in i ett regionalt samband. Tal. hade själv för länge sen framgrävt en mängd lokaler i Vilhelmina s:n, sedan ha nya kommit fram där, och slutligen har Erik Granlund i Stenseletrakten funnit likartade. Liknande sediment känner man också från nedre delen av Ströms Vattudal. Där förhållandena kunnat närmare undersökas, tyckes även vid dessa nordligare förekomster föreligga analoga skillnader i moränens sammansättning ovan och under sedimenten. Sedimentens ställvis betydande mäktighet förutsätta en avsevärd avsättningstid, i Vilhelminatrakten åtminstone några hundra år. De markera tydligen ett problem av ganska regional betydelse och i hög grad förtjänt att upptagas till detaljerad utredning.

Vid mötet utdelades nr 432 av Förhandlingarna.

## Mötet den 10 mars 1943.

Närvarande 36 personer.

Mötet hade anordnats tillsammans med Geografiska Förbundet.

Hr G. Lundqvist höll ett av skioptikonbilder belyst föredrag om Den regionala fördelningen av Norrlands lösa jordarter.

Föredraget utgjorde en granskning av de skilda jordartstypernas förekomst samt en beskrivning till föredr:s karta över Norrlands jordarter i »Norrland», utg. av Geografiska Förbundet (Ymer, 1942).

Med anledning av föredraget yttrade sig hrr Tamm, Simon Johansson Eneroth, Beskow, Caldenius, Halden och föredraganden.

## Mötet den 1 april 1943.

Närvarande 38 personer.

Ordföranden, hr Helmer Hedström, öppnade mötet med följande anförande:

Sedan vårt föregående sammanträde har meddelande ingått, att två av Föreningens utländska medlemmar avlidit.

Sir Henry Miers avled den 10 december i sitt hem i West Hampstead i en ålder av 85 år. Han var ursprungligen humanist, med gedigen utbildning från Eton och Oxford, men blev därefter matematiker. Ifrån Oxford kom han till British Museum's mineralogiska avdelning, blev sedermera lärare i kristallografi och slutligen, år 1895, professor i mineralogi i Oxford. År 1908 blev han rektor vid University of London och 1915 vice kansler vid universitetet i Manchester, där han kvarstod till pensioneringen 1926. Under senare år var han flitigt anlitad av brittiska myndigheter för utredningar i museifrågor. Han blev medlem av Royal Society 1896 och adlades 1912. I vår förening var han ständig ledamot sedan år 1894.

Den 27 december avled Frank Dawson Adams, emeritus professor i geologi och vice rektor vid McGill University i Montreal i en ålder av 83 år. Han var född i Montreal, studerade vid McGill University och blev, efter några år i Canadas Geologiska Undersökning, docent vid McGill University och slutligen år 1893 professor i geologi vid samma universitet. Under de följande tjugu åren ägnade han sig vid sidan av lärarkallet åt urbergsgeologiska studier inom den stora »Praecambrian Shield» i Canada, och han kom under denna tid att vinna erkännande som en av världens främsta urbergsgeologer. Under sina studier av speciellt gnejsbergarterna kom han på tanken att genom laboratorieförsök söka efterbilda de förhållanden, som utformat dessa bergarter, och han igångsatte tidigt en lång serie experiment, vars resultat sedermera framlades i en rad märkliga arbeten, om bl. a. bergarters flytning under tryck (1901), bergarternas elastiska konstanter (1906) m. fl. Dessa Adams' experiment voro de första, som någonsin givit kvantitativa data för studiet av dessa och närliggande problem, och först långt senare ha liknande arbeten upptagits av andra. Sedan Adams lämnat undervisningen vid McGill University, har han utgivit flera arbeten, varav det sista så sent som 1938 (»Birth and Development of the Geological Sciences»). Han blev medlem av Royal Society 1907. Sedan 1911 var han korresponderande ledamot i vår förening.

Till nya ledamöter av Föreningen hade styrelsen invalt gruvingenjören i Norra bergmästaredistriktet bergsingenjör Y. Hagerman, Luleå, föreslagen av hr Bergwall, assistenten vid Mineralogisk Museum mag. scient. Hans Clausen, Köpenhamn, föreslagen av hrr Noe-Nygaard och Troedsson, samt fil. stud. Sten Sture Paterson, Stockholm, föreslagen av hr Troedsson.

Från Fullmäktige i Jernkontoret hade erhållits ett bidrag av 1,000 kronor till fortsatt utgivande av Förhandlingarna under år 1943.

Hr Adamson höll föredrag om En oversikt over det alkaline bergartsområde ved Norra Kärr i Småland. En uppsats i ämnet är avsedd att införas i ett senare häfte av Förhandlingarna.

Med anledning av föredraget yttrade sig hrr A. Gavelin, Backlund, Quensel, J. Eklund, N. Magnusson och Geijer samt föredraganden.

## Geolognytt.

Förste byråingenjör Ragnar Stahre har utnämnts till bergmästare i Södra bergmästaredistriktet.

Docent Alfred Rosenkrantz, Köpenhamn, har utnämnts till professor i geologi vid Danmarks tekniske Höjskole (Polyteknisk Læreanstalt) från den 1 april 1943.

Professor Helge Backlund och professor Pentti Eskola ha av Geologische Vereinigung i Frankfurt a. M. tilldelats Steinmann-medaljen.

K. Vetenskapsakademien har ur Hierta-Retzius-stiftelsens stipendiefond tilldelat prof. L. von Post för att avsluta fältarbeten vid kvartärgeologisk undersökning av Viskadalen ett understöd av 4 000 kr.; ur Hierta-Retziusfonden för vetenskaplig forskning lektor Gunnar Erdtman för utarbetande av monografi över fanerogamernas och kärlkryptogamernas pollen och sporer 2 500 kr., docent Carl Caldenius för kvartärgeologiska undersökningar inom sydvästra Sverige 5 500 kr. samt fil. lic. Erik Jarvik för framställning av plansch- och textfigurer till ett arbete om neurala endokraniet hos Eusthenopteron 3 400 kr. Av akademiens resestipendier till yngre naturvetenskapsmän för undersökning av landets naturförhållanden har fil. kand. Bengt Collini för en undersökning av Visingsöformationen erhållit 250 kr.

Professor G. De Geer har från Stiftelsen Lars Hiertas minne erhållit ett anslag av 3 500 kr. till avlöning av biträde för renritning av diagram och kartor över landisens recession i södra Skandinavien.

Flormanska priset har av K. Vetenskapsakademien tilldelats fil. lic. Erik Jarvik för hans arbete »On the structure of the snout of crossopterygians and lower gnathostomes in general».

Vitterhetsakademien har tilldelat fil. lic. S. Florin 4 000 kr. för tryckning av ett arbete »Vråkulturen, en studie över Mälardalens äldsta bondekultur».

Svenska Sällskapet för antropologi och geografi har ur Andréefonden tilldelat docent Sven Björnsson, Lund, 1 328 kr. för geomorfologiska studier inom Sydsvenska höglandets randzon mot Östgötaslätten; docent Arne Sandell, Lund, 900 kr. för fortsatt tektonisk-morfologisk undersökning av västra Dalarnas porfyr- och sandstensområden samt fil. lic. Olof Ängeby, Lund, 600 kr. för fortsatta geomorfologiska studier i nordvästra Jämtland. Den sistnämnde har för samma ändamål erhållit 500 kr. av K. Fysiografiska Sällskapet i Lund.

Från Kungl. Fysiografiska Sällskapet i Lund (stipendier ur Jubileumsfonderna och Tornbladsfonden) har vidare utdelats: till fil. lic. Lars Bjerning, för studier över Skånes jord- och stenindustri, 200 kr.; docent Sven Björnsson, för en undersökning av moränens terrängformer inom södra Östergötlands skogstrakter, 100 kr.; samt fil. lic. Carl Erik Nordenskjöld, för fortsatta morfologiska studier inom övergångsområdet mellan Kalmarslätten och Tjust, 400 kr.

Längmanska kulturfondens nämnd har utdelat anslag till bl. a. fil. dr J. Alin, Göteborg, för avvägning av stenåldersboplatser och fornstrandlinjer i Bohuslän samt prof. L. von Post för ritningsarbeten i samband med slutförandet av hans kvartärgeologiska undersökning av Viskadalen.

För vinnande av fil. doktorsgrad försvarade fil. lic. K. E. Bergsten den 20 april å Geografiska institutionen i Lund en avhandling med titeln Isälvsfält kring norra Vättern.

Den 25 maj 1943 försvarar fil. lic. Brian Mason å Stockholms högskolas Mineralogiska institut en i detta häfte intagen avhandling med titeln Mineralogical aspects of the system $FeO\text{-}Fe_2O_3\text{-}MnO\text{-}Mn_2O_3$. Opponenter äro professor H. von Eckermann och statsgeologen dr O. Ödman.

## Sveriges geologiska undersöknings fältarbeten 1943.

Museiföreståndaren A. H. Westergård leder undersökningarna över alunskiffer på Öland.

Statsgeologen S. Johansson utför agrikulturgeologiska och hydrogeologiska specialundersökningar.

Statsgeologen R. Sandegren utför kartering på kartbladet Söderfors. Extrageolog: O. Claesson.

Statsgeologen N. Sundius undersöker tillgångar av kvarts, fältspat och glimmer, samt av urbergets karbonatbergarter i Södermanland och Närke, och utför nödiga kompletteringar å berggrundskartan över Stockholmstrakten.

Statsgeologen G. Lundqvist utför kartering på kartbladet Avesta, rekognoscerar för jordartskartan över Kopparbergs län samt meddelar instruktion för nya kartbladsrekognoscörer. Extrageologer: å kartbl. Avesta B. Collini, G. Flodkvist, E. Fromm, S. Gaunitz och E. Rytterberg, vid länskarteringen C. Larsson.

Statsgeologen B. Asklund övervakar berggrundskarteringen å kartbladet Söderfors, reviderar specialkarteringen av Bohusläns granitområde, samt utför undersökningar inom andra stenindustriområden. Extrageolog: P. H. Lundegårdh (för Bohuslän).

Statsgeologen G. Ekström reviderar jordartskarteringen på kartbladet Lund samt utför hydrogeologiska specialundersökningar. Extrageolog: N. Linnermark.

Statsgeologen O. Ödman utför malmgeologiska specialundersökningar inom Norrbottens län.

Statsgeologen S. Hjelmqvist övervakar berggrundskarteringen på kartbladen Avesta och Falun samt påbörjar översiktskartering av berggrunden inom sydvästra delen av Kopparbergs län.

Geologen J. Eklund leder undersökningarna över alunskiffer i Närke.

Geologen P. Thorslund leder undersökningarna över alunskiffer i Östergötland.

Geologen S. Gavelin utför malmgeologiska specialundersökningar inom Västerbottens och Norrbottens län. Extrageolog: O. Gabrielsson.

Geologen O. Kulling fortsätter karteringen på kartbladet Falun samt utför preliminär rekognoscering av jordarterna inom Storsjöbygden i Jämtland. Extrageologer å kartbl. Falun: A. Klementsson, E. Åhman och J. Öster.

Geologen W. Larsson reviderar berggrunden på kartbladet Vårvik.

Gruvingenjören K. A. Barkenberg leder de gruvtekniska arbetena i Norrland.

Assistenten S. Werner leder de geofysiska fältarbetena i Norrland.

I fältarbetena deltaga vidare Professor N. H. Magnusson (revisionsarbeten på kartbl. Vårvik), Docent N. G. Hörner (rekognoscering för ny upplaga av kartbl. Uppsala) och Docent T. Krokström (berggrundskartering i Myrhedentrakten).

Vidare komma, efter särskilt meddelade instruktioner, praktiskt-geologiska undersökningar i beredskapssyfte att företagas i mån av behov.

**il. Dr NAIMA SAHLBOM**

**Speciallaboratorium**

för

**lineral-, Bergarts- och Vatten-analyser.**
**adioaktivitetsmätningar m. m.**

Telefon 10 33 72
**riksbergsgatan 13 Stockholm**

**GEOLOGIENS GRUNDER**

*av professor Wilhelm Ramsay,*

3:e upplagan, omarbetad av *P. Eskola, Bror Asklund, G. Troedsson, M. Sauramo* m. fl. 2 delar. Med 529 illustrationer. 1931. 890 sid. Två präktiga volymer i stort oktavformat. Till salu i varje bokhandel. Häftad kr. 24: —, i två klotband kr. 30: —, i två halvfranska band kr. 36: —

**Vetenskapliga och Litterära Verk A.-B.**
**Stockholm**

## Meddelande från redaktionen.

Enligt de nya postbestämmelser, som trädde i kraft den 1 april 1943, få på korrekturen, om dessa befordras såsom korsband, inga anteckningar göras, som kunna tolkas såsom meddelanden. Således får exempelvis icke utsättas uppgifter om upplaga, det antal korrekturexemplar som önskas, anteckningar om omsättningar eller ändringar av eventuella delar i texten, graden av skyndsamhet e. d.

## SVERIGES GEOLOGISKA UNDERSÖKNINGS SENAST UTKOMNA PUBLIKATIONER ÄRO:

### Ser. Aa. Geologiska kartblad i skalan 1 : 50 000 med beskrivningar.

| | | |
|---|---|---|
| N:o 178 | Gävle av R. Sandegren, B. Asklund och A. H. Westergård 1939 | 4,00 |
| » 179 | Forshaga av R. Sandegren och N. H. Magnusson 1937 | 4,00 |
| » 180 | Fårö av H. Munthe, J. E. Hede och G. Lundqvist 1936 | 4,00 |
| » 181 | Smedjebacken av G. Lundqvist och S. Hjelmqvist 1937 | 4,00 |
| » 182 | Lidköping av S. Johansson, N. Sundius och A. H. Westergård 1943 | 4,00 |
| » 183 | Visby och Lummelunda av G. Lundqvist, J. E. Hede och N. Sundius 1940 | 4,00 |
| » 184 | Hedemora av G. Lundqvist och S. Hjelmqvist 1941 | 4,00 |

### Ser. C.

#### Årsbok 35 (1941)

| | | |
|---|---|---|
| N:o 438 | Ödman, Olof H., Geology and ores of the Boliden deposit, Sweden. With 48 plates. 1941 | 8,00 |
| » 439 | Du Rietz, T., Nyare undersökningar inom Remdalens malmtrakt och dess omgivningar. Med 4 tavlor. 1941 | 3,00 |
| » 440 | Sahlström, K. E., Jordskalv i Sverige 1936—40. Med en karta. Resumee: Erdbeben in Schweden 1936—40. 1941 | 0,50 |
| » 441 | Sundius, N., Oljeskiffrar och skifferoljeindustri. 1941 | 3,00 |
| » 442 | Westergård A. H. Skifferborrningarna i Yxhultstrakten i Närke 1940. Med 3 tavlor. Kemiska analyser av G. Assarsson. Summary: Borings through the Alum shale in the neighbourhood of Yxhult in Närke made in 1940 | 1,00 |
| » 443 | Gavelin, S., Relations between ore deposition and structure in the Skellefte district. 1942 | 0,50 |

#### Årsbok 36 (1942)

| | | |
|---|---|---|
| N:o 444 | Ödman, O. H., Copper ores of the ›Red beds› type from Visingsö, Sweden. 1942 | 1,00 |
| » 445 | Kulling, O., Grunddragen av fjällkedjerandens bergbyggnad inom Västerbottens län. Med 1 karta. 1942 | 6,00 |
| » 446 | Lundqvist, G., Sjösediment och deras bildningsmiljö. 1942 | 1,00 |
| » 447 | Grip, E. and Ödman, O. H., The telluride-bearing andalusite-sericite rocks of Mångfallberget at Boliden, N. Sweden. 1942 | 1,00 |
| » 448 | Du Rietz, T., Kvartsitskollorna i Ormsjö-Tåsjötrakten. Med en karta. 1943 | 1,00 |
| » 449 | Hjelmqvist, Sven, Stribergs malmfält. Geologisk beskrivning. Med 3 tavlor. Zusammenfassung: Der Striberger Erzbezirk. Geologische Beschreibung. 1942 | 3,00 |
| » 451 | Brotzen, F., Die Foraminiferengattung Gavelinella nov. gen. und die Systematik der Rotaliiformes. Mit 1 Tafel. 1942 | 2,00 |

#### Årsbok 37 (1943)

| | | |
|---|---|---|
| N:o 452 | Ödman, O. H., Geology of the copper deposits at Laver. N. Sweden with 2 plates. 1943 | 1,00 |
| » 453 | Hjelmqvist, Sven, Die Natronreiche Randzone des Granitmassivs nördlich von Smedjebacken. Ein Beitrag zum Studium der Granitbildung. 1943 | 1,00 |

### Ser. Ca.

| | | |
|---|---|---|
| N:o 34 | Molin, K., A general earth magnetic investigation of Sweden carried out during the period 1928—1934 by the Geological survey of Sweden. Part 4. Vertical intensity. With 5 plates. 1942 | 10,00 |

Distribueras genom Generalstabens Litografiska Anstalt. Stockholm 1.

*Diamond Core Drilling*
*Cement Grouting*

*Contractors*
*and*
*Manufacturers of machinery*

*Svenska Diamantbergborrnings*
*Aktiebolaget*
*Kungsgatan 44*
*Stockholm C.*

---

**GEOLOGICAL INVESTIGATIONS**
and
**GEOPHYSICAL PROSPECTING**
**FOR ORE AND OIL**

by means of
Electrical, Magnetic, Gravimetric,
Seismic Methods

AKTIEBOLAGET ELEKTRISK MALMLETNING
*(The Electrical Prospecting Company)*
Kungsgatan 44, Stockholm, Sweden.
*Write for Publications.*

**Geologiska Föreningens i Stockholm Förhandlingar** utkomma med 4 häften årligen. Prenumeration mottages genom Nordiska bokhandeln, Stockholm.

| | Generalregister till | Generalregister till |
|---|---|---|
| Bd 1—31 à 20 kr. | Bd 1—5 à 3 kr. | Bd 22—31 à 6 kr. |
| » 32 » 60 » | » 6—10 » 4 » | » 32—41 » 6 » |
| » 33—64 » 20 » | » 11—21 » 6 » | » 42—50 » 6 » |
| | | » 51—60 » 6 » |

Lösa häften av alla banden till pris beroende på häftenas omfång.

Medlemmar av Föreningen erhålla genom skattmästaren de äldre banden av Förhandlingarna och Generalregistret till hälften av det ovan upptagna bokhandelspriset. Å lösa häften lämnas ej prisnedsättning. (Styrelsens beslut d. $^{27}/_{10}$ 1922.)

**Geologiska Föreningens sekreterare, Docenten G. Troedsson, träffas i Föreningens angelägenheter i bostaden Bragev. 29, Djursholm, kl. 17—18, Tel. 55 20 10. Efter överenskommelse per telefon kan sekreteraren även träffas å Sveriges geologiska undersökning eller å Stockholms högskolas Geologiska institut.**

Föreningens **ordinarie möten** äga rum första helgfria torsdag i månaderna februari, mars, april, maj, oktober, november och december. Dagen för januarimötet bestämmes å decembersammankomsten. Anslag om föredragningslistan finnas minst 3 dagar före sammanträdet uppsatta på anslagstavlorna å följande offentliga institutioner: Stockholms Högskola, Tekniska Högskolan, Bergshögskolan, Jernkontoret, Sv. Geol. Undersökning, Statens Meteorologisk-Hydrografiska Anstalt, Statens Skogsförsöksanstalt, Skogshögskolan, Statens Järnvägars Geotekniska avd., Statens väginstitut, Upsala Univ:s Geolog., Geogr., Paleont. och Växtbiol. inst. samt Lunds Univ:s Geol. och Geogr. inst.

Personlig kallelse till sammanträdena utfärdas på därom gjord framställning till sekreteraren.

Häftena utdelas sammanträdesdagarna i januari, mars, maj och november.

**Uppsatser**, avsedda att införas i Förhandlingarna, insändas till Föreningens sekreterare, Bragevägen 29, Djursholm 2. Åtföljande tavlor och figurer böra vara fullt färdiga till reproduktion, då de jämte uppsatsen sändas.

I Förhandlingarna må uppsatser — förutom på skandinaviskt språk — införas på engelska, franska eller tyska; dock vare författare skyldig att i de fall då Styrelsen anser sådant önskvärt bifoga en resumé på skandinaviskt språk.

Manuskript, skrivet på främmande språk, skall vara granskat av sakkunnig språkman, varom meddelande göres till sekreteraren.

Därest korrektionskostnaderna för införd uppsats uppgå till mera än 16 kronor pr tryckark, vare författare skyldig att erlägga det överskjutande beloppet, såvida det uppgår till minst 10 kr. pr uppsats.

Författare erhåller gratis av införda uppsatser 75 separat i omslag utan titel; ytterligare ex. samt ev. omslagstitel betalas av förf. Av notiser, anmälanden och föredragsreferat lämnas separat endast efter särskild överenskommelse.

**Referat** honoreras sålunda (Fören. beslut $^{7}/_{12}$ 1911):

1:sta sidan eller del därav . . . . . . . . efter 20 öre pr tryckrad.
2:dra » » » » . . . . . . . . » 15 » » »
3:dje » » » » . . . . . . . . » 10 » » »
Följande sidor honoreras icke.

Anmälan om **föredrag** göres i god tid hos sekreteraren.

**Ledamöternas årsavgifter**, vilka enligt § 7 av Föreningens stadgar skola vara inbetalda senast den 1 mars, insändas till Föreningens skattmästare, Dr K. E. Sahlström, Sveriges Geologiska Undersökning, Stockholm 50, till vilken Föreningens ledamöter även torde insända uppgifter om ändringar av adresser och titlar.

Årsavgiften utgör kr. 15: —, avgift såsom ständig ledamot kr. 200: —. Ledamot, som under en följd av minst 20 år erlagt årlig ledamotsavgift, kan bliva ständig ledamot mot en avgift av kr. 100: —.